FINAL

Combustion 2000
Phase II

DE-AC22-95PC95144--28

Quarterly Progress Report

April 1 - June 30, 2000

Prepared for

Federal Energy Technology Center
Pittsburgh, Pennsylvania

United Technologies Research Center
411 Silver Lane, East Hartford, Connecticut 06108

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ABSTRACT

This report presents work carried out under contract DE-AC22-95PC95144 "Combustion 2000 - Phase II." The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◊ thermal efficiency (HHV) ≥ 47%
- ◊ NOx, SOx, and particulates ≤ 10% NSPS (New Source Performance Standard)
- ◊ coal providing ≥ 65% of heat input
- ◊ all solid wastes benign
- ◊ cost of electricity ≤ 90% of present plants

Phase I, which began in 1992, focused on the analysis of various configurations of indirectly fired cycles and on technical assessments of alternative plant subsystems and components, including performance requirements, developmental status, design options, complexity and reliability, and capital and operating costs. Phase I also included preliminary R&D and the preparation of designs for HIPPS commercial plants approximately 300 MWe in size.

Phase II, had as its initial objective the development of a complete design base for the construction and operation of a HIPPS prototype plant to be constructed in Phase III. As part of a descoping initiative, the Phase III program has been eliminated and work related to the commercial plant design has been ended. The rescoped program retained a program of engineering research and development focusing on high temperature heat exchangers, e.g. HITAF development (Task 2); a rescoped Task 6 that is pertinent to Vision 21 objectives and focuses on advanced cycle analysis and optimization, integration of gas turbines into complex cycles, and repowering designs; and preparation of the Phase II Technical Report (Task 8). This rescoped program deleted all subsystem testing (Tasks 3, 4, and 5) and the development of a site-specific engineering design and test plan for the HIPPS prototype plant (Task 7).

Work reported herein is from:

- ◊ Task 2.2.4 Pilot Scale Testing
- ◊ Task 2.2.5.2 Laboratory and Bench Scale Activities

EXECUTIVE SUMMARY

This report represents work carried out under contract DE-AC22-95PC95144 "Combustion 2000: Phase II." The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◊ ≥ 47% thermal efficiency (HHV)
- ◊ NOx, SOx, and particulates ≤ 10% NSPS
- ◊ coal providing ≥ 65% of heat input
- ◊ all solid wastes benign
- ◊ cost of electricity ≤ 90% of present plant

Work reported in this report is from Task 2.2 HITAF Air Heaters.

Data and observations from coal-fired tests completed in March 2000 are documented in this report and compared with previous data where appropriate. The data, results, and observations are included in this report because they were not available for inclusion in the quarterly technical progress report for January through March 2000. The high-density refractory liner in the slagging furnace was replaced in May, and the new refractory was cured in early June. Once refractory curing was completed, the radiant air heater (RAH) panel was reassembled using a complete set of new side rails and Monofrax M and Kyocera tiles. In addition, the performance of the RAH panel was evaluated during an SFS test from June 10 to 27. However, results from the June test are incomplete at this time and will be summarized in the next quarterly technical progress report.

Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through May 2000

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	1904	1382	3286
CAH Tube Bank	1589	1349	2938
RAH Panel	1301	1302	2603

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COMBUSTION 2000 PROJECT

INTRODUCTION

The High Performance Power Systems (HIPPS) electric power generation plant integrates a combustion gas turbine and heat recovery steam generator (HRSG) combined cycle arrangement with an advanced coal-fired boiler. The unique feature of the HIPPS plant is the partial heating of gas turbine (GT) compressor outlet air using energy released by firing coal in the high temperature advanced furnace (HITAF). The compressed air is additionally heated prior to entering the GT expander section by burning natural gas. Thermal energy in the gas turbine exhaust and in the HITAF flue gas are used in a steam cycle to maximize electric power production. The HIPPS plant arrangement is thus a combination of existing technologies (gas turbine, heat recovery boilers, conventional steam cycle) and new technologies (the HITAF design including the air heaters, and especially the heater located in the radiant section).

The HITAF provides heat to the compressor outlet air using two air heaters, a convective air heater (CAH), and a radiant air heater (RAH). The HITAF is a slagging furnace which contains the radiant air heater, as well as waterwalls and steam drum for the high pressure (HP) steam system. Hot flue gas leaving the HITAF furnace passes over the CAH prior to entering a heat recovery steam generator (HRSG). Hot exhaust gas from the gas turbine is ducted to another HRSG in a typical combined cycle arrangement. The HITAF, gas turbine and HRSGs are configured to achieve the required high efficiency of the HIPPS plant.

The key to the success of the concept is the development of integrated combustor/air heater that will fire a wide range of US coals with minimal natural gas and with the reliability of current coal-fired plants. The compatibility of the slagging combustor with the high temperature radiant air heater is the critical challenge.

TASK 2.2.4 – PILOT-SCALE TESTING

Pilot-scale activities this past quarter were performed under Task 2.2.4.3, HITAF Testing. They involved SFS maintenance, modifications and repairs following completion of a 200-hr coal-fired SFS test in late March, replacement of the high-density refractory in the slagging furnace, curing of the new furnace refractory, and disassembly and reassembly of the RAH panel. Instrumentation work this past quarter focused on routine maintenance and calibration of SFS components. Other activities were limited to miscellaneous maintenance items in support of overall SFS operation, selection and procurement of a bituminous coal for the June test, and completion of a 200-hr coal-fired SFS test on June 27, 2000.

Description of Pilot-Scale SFS

Exhibit 2-1 is a simplified illustration of the overall slagging furnace system.

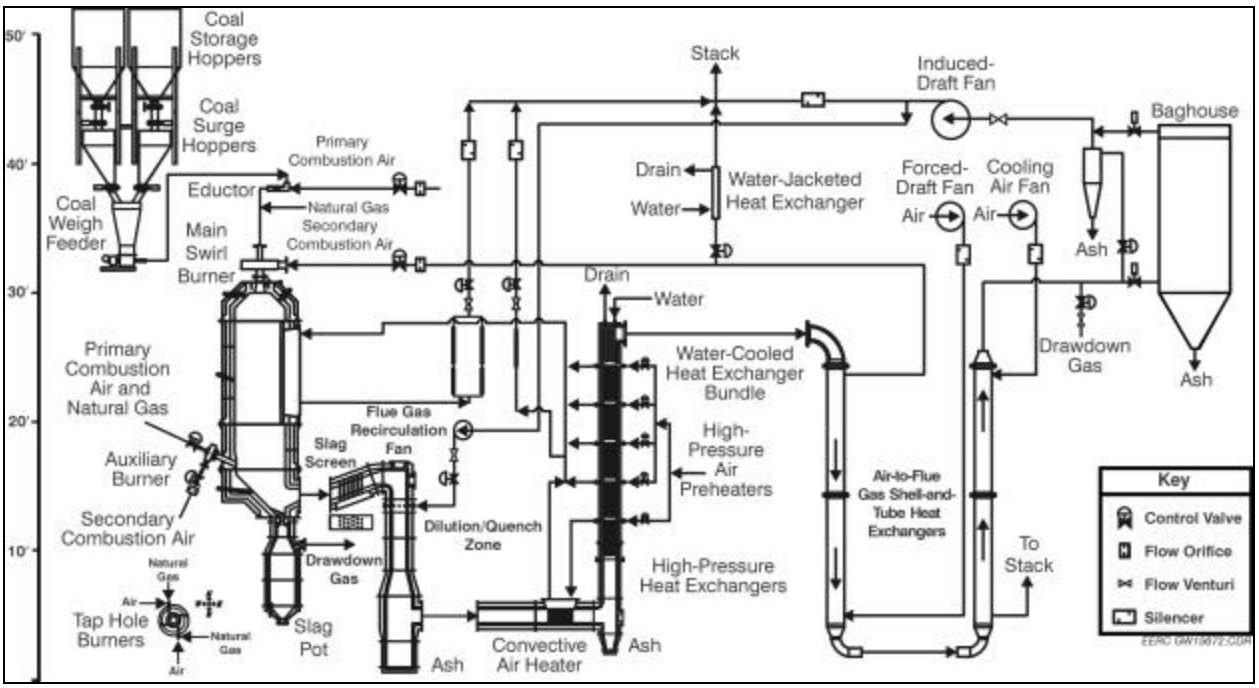

Exhibit 2-1 Combustion 2000 Slagging Furnace and Support System

Slagging Furnace

The pilot-scale slagging furnace is intended to be as fuel-flexible as possible, with maximum furnace exit temperatures of 2700° to 2900°F (1483° to 1593°C) to maintain the desired heat transfer to the RAH panel and slag flow. The furnace has a nominal firing rate of 2.5 MMBtu/hr (2.6 × 106 kJ/hr) and a range of 2.0 to 3.0 MMBtu/hr (2.1 to 3.2 × 106 kJ/hr) using a single burner. The design is based on Illinois No. 6 bituminous coal (11,100 Btu/lb or 25,800 kJ/kg) and a nominal furnace residence time of 3.5 s. Flue gas flow rates range from roughly 425 to 645 scfm (12.0 to 18.6 m3/min), with a nominal value of 530 scfm (15 m3/min), based on 20% excess air. Firing a subbituminous coal or lignite increases the flue gas volume, decreasing residence time to roughly 2.6 s. However, the high volatility of the low-rank fuels results in high combustion efficiency (>99%). The furnace is oriented vertically (downfired) and based the burner design on that of a swirl burner used on two smaller pilot-scale pulverized coal (pc)-fired units (600,000 Btu/hr

[633,000 kJ/hr]). Slagging furnace internal dimensions are 47 in. (119 cm) in diameter by roughly 16 ft (4.9 m) in total length.

The vertically oriented furnace shell was designed to include four distinct furnace sections. The top section of the furnace supports the main burner connection, while the upper-middle furnace section provides a location for installation of the RAH panels. The lower-middle furnace section supports the auxiliary gas burner; the bottom section of the furnace includes the furnace exit to the slag screen as well as the slag tap opening. Flue gas temperature measurements are made using two Type S thermocouples protruding 1 in. (2.5 cm) into the furnace through the refractory wall and three optical pyrometers (flame, flue gas along the furnace wall near the RAH panel, and flue gas at the furnace exit). Furnace temperature is also measured using thermocouples located at the interface between the high-density and intermediate refractory layers as well as between the intermediate and insulating refractory layers. A pressure transmitter and gauges are used to monitor static pressures in order to monitor furnace performance. These data (temperatures and pressures) are automatically logged into the data acquisition system and recorded manually on data sheets on a periodic basis as backup.

The slag tap is intended to be as simple and functional as possible. To that end, the design is a simple refractory-lined hole in the bottom of the furnace. The diameter of the slag tap is nominally 4 in. (10 cm), with a well-defined drip edge. A two-port natural gas-fired taphole burner is used to maintain slag tap temperature for good slag flow. To minimize heat losses, slag is collected in an uncooled, dry container with refractory walls. When the slag tap had plugged in the first couple years of the project, the plug was typically removed on-line after a switch was made to natural gas firing for a short period of time (2 hr) in the main burner. In the last 12 months, an approach has been developed and personnel safety equipment acquired to permit the removal of slag tap plugs on-line while coal is fired. During the March test period, the slag tap plugged once, forcing a short switch to natural gas firing and removal of the slag pot and cleaning of the tap. Removal of the slag pot to facilitate slag tap cleaning was required four additional times to prevent a potential plug, although coal firing was maintained during these periods.

The refractory walls in the slagging furnace are composed of three layers of castable refractory. They consist of an inner 4-in. (10.2-cm) layer of high-density (14-Btu-in./ft2°F-hr or 2.0-W/m-K) slag-resistant material, 4 in. (10.2 cm) of an intermediate refractory (4.0 Btu-in./ft2°F-hr or 0.6 W/m-K), and a 3.25-in. (8.3-cm) outer layer of a low-density insulating refractory (1.3 Btu-in./ft2°F-hr or 0.2 W/m-K). Three refractory layers were selected as a cost-effective approach to keeping the overall size and weight of the furnace to a minimum while reducing slag corrosion and heat loss. Table 2-1 summarizes properties for refractory material used in the SFS. The condition of the high-density refractory in the top and bottom sections of the furnace was poor following the test completed in March 2000 because of slag attack. Therefore, the high-density refractory in the slagging furnace was replaced prior to installing new side rails and Kyocera tiles in the RAH panel and performing a SFS test in June.

Main and Auxiliary Burners

The main burner is natural gas- and pulverized fuel-capable. The basic design is an International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator, which uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl. Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NOx. Carbon conversion has been >99% when bituminous and subbituminous coal and lignite are fired. High carbon conversions can be obtained at low swirl settings because of the high operating temperature and adequate

residence time. Combustion air flow rates through the main burner range from about 400 to 600 scfm (11 to 17 m3/min), depending on furnace firing rate and the fuel type (bituminous, subbituminous, or lignite) fired.

An auxiliary gas burner (maximum firing rate of 850,000 Btu/hr or 896,750 kJ/hr) is located near the furnace exit to control furnace exit temperature, ensuring desired slag flow from the furnace and the slag screen. This auxiliary burner is used to compensate for heat losses through the furnace walls, sight ports, and RAH test panel. Use of the auxiliary gas burner is beneficial during start-up to reduce heatup time and to prevent slag from freezing on the slag screen when the switch is initially made to coal firing.

Table 2-1 Refractory Properties

Refractory:	Plicast Cement-Free 99V KK/99V[1]	Plicast Cement-Free 98V KK/98V[1]	Plicast Cement-Free 96V KK/96V[1]	Narco Cast 60	Plicast LWI-28	Plicast LWI-20	Harbison-Walker 26
Function	High density	High density	High density	High density	Insulating	Insulating	Insulating
Service Limit, °F	3400	3400	3300	3100	2800	2000	2600
Density, lb/ft^3	185	185	185	145	80	55	66
K, Btu-in./ft^2°F-hr @ 2000°F	14.5	14.5	14.0	6.5	4.0	NA[2]	2.2
K, Btu-in./ft^2°F-hr @ 1500°F	14.7	14.7	14.2	6.0	3.0	1.7	1.9
K, Btu-in./ft^2°F-hr @ 1000°F	15.5	15.5	15.0	5.6	2.7	1.3	.7
Hot MOR[3] @ 2500°F, psi	650	750	1400	NA	NA	NA	NA
Hot MOR @ 1500°F, psi	–	–	2000	1000	250	100	110
Cold Crush Strength @ 1500°F, psi	–	–	10000	NA	750	400	350
Typical Chemical Analysis, wt% (calcined)							
Al_2O_3	99.6	98.6	95.5	62.2	54.2	39.6	53.8
SiO_2	0.1	1.0	3.8	28.0	36.3	31.5	36.3
Fe_2O_3	0.1	0.1	0.1	1.0	0.8	5.4	0.5
TiO_2	0.0	0.0	0.0	1.7	0.5	1.5	0.6
CaO	0.1	0.1	0.1	2.8	5.7	19.5	7.2
MgO	0.0	0.0	0.0	0.1	0.2	0.8	0.2
Alkalies	0.2	0.2	0.2	0.2	1.5	1.4	1.4

[1] The “KK” designation indicates the presence of fibers that promote dewatering during curing. [2] Not applicable.

[3] Modulus of rupture.

Radiant Air Heater Panel

A key design feature of the furnace is accessibility for installation and testing of an RAH panel. The furnace will accept a panel with a maximum active size of 1.5 × 6.4 ft (0.46 × 1.96 m). This size was selected on the basis of panel-manufacturing constraints identified by UTRC as well as a desire to minimize furnace heat losses. Flame impingement on the RAH panel is not necessarily a problem. Process air for the RAH panel is provided by an air compressor having a maximum delivery rate of 510 scfm (14.4 m^3/min) and a maximum stable delivery pressure of 275 psig (19 bar). Backup process air is available from a smaller compressor at a maximum delivery rate of 300 scfm (8.5 m^3/min) and pressure of <100 psig (<7 bar). A tie-in to a nitrogen system is also available as a backup to the air compressor system. In the event of a failure of inlet process air piping, a backflow emergency piping system was installed so that overheating of the RAH panel could be avoided. UTRC designed and fabricated the RAH test panel.

Slag Screen

The slag screen design for the pilot-scale SFS is the result of a cooperative effort between EERC, UTRC, and PSI personnel. The primary objective for the pilot-scale slag screen is to reduce the concentration of ash particles entering the convective air heater (CAH). The walls of the slag screen consist of two refractory layers. The inner, high-density layer is a Plicast Cement-Free 98V with an outer insulating layer of Harbison-Walker Castable 26. The high-density refractory is 2.25 in. (5.7 cm) thick in the sidewalls and 4 in. (10.2 cm) thick in the roof and floor of the slag screen. The insulating refractory is 3.75 in. (9.5 cm) thick in the sidewalls, roof, and floor. A Plicast LWI-28 refractory was used around the sight ports in the wall of the slag screen. Properties for the high-density and insulating refractory selected for use in the slag screen are summarized in Table 2-1. The current slag screen design permits the use of a maximum of 18 tubes, 1.5 in. (3.8 cm) in diameter in a six-row staggered array. The number of tubes in use for a given SFS test is dependent on the ash fusion properties of the fuel ash. Water-cooled surfaces were installed inside of the refractory tubes to cool the tubes and reduce the erosion/corrosion observed during shakedown tests. Specific details concerning slag screen modifications and performance this quarter are addressed later in this report.

Dilution/Quench Zone

The dilution/quench zone design was a cooperative effort between the EERC and UTRC. It is refractory-lined and located immediately downstream of the slag screen and upstream of the CAH duct. It is oriented vertically and has a 1.17-ft (0.36-m) inside diameter in the area of the flue gas recirculation (FGR) nozzles, expanding to 2 ft (0.6 m) below the nozzles to provide adequate residence time within duct length constraints. The duct section containing the flue gas recirculation nozzles is a spool piece to accommodate potential changes to the size, number, and orientation of the flue gas recirculation nozzles.

Routine cleaning of the dilution/quench zone has been required during each weeklong bituminous and subbituminous coal-fired test. A pressure transmitter is used to monitor and record differential pressure, as an indication of slag deposition in the dilution/quench zone. On the basis of observations made during an August 1998 test and the frequent cleaning required, the EERC modified the spool piece section of the dilution/quench zone. The specific modification involved the addition of a water-cooled wall around the FGR nozzles. This water-cooled wall appears to embrittle the slag deposits that form in this area, making them more prone to spontaneous shedding and generally easier to remove on-line. Performance observations during the March test are summarized later in this report.

Convective Air Heater

In the CAH design the flue gas flow rate to the CAH tube bank has been calculated to range from 3553 to 4619 acfm at 1800°F (101 to 131 m^3/min at 982°C). A rectangular inside duct dimension of 1.17 ft^2 (0.11 m^2) results in a flue gas approach velocity of 50 to 73 ft/s (15 to 22 m/s) to the CAH. The CAH originally consisted of twelve 2-in. (5-cm)-diameter tubes installed in a staggered three-row array. The first five tubes in the flue gas path were uncooled ceramic material, with the remaining seven tubes cooled by heated process air. The uncooled ceramic tubes were replaced in May 1998 with uncooled stainless steel tubes because the ceramic tubes were repeatedly damaged when the tube bank was removed from the duct.

In September 1998, the uncooled tubes were again replaced. The replacement tubes represented three high-temperature alloy types (Incoloy MA956, Incoloy MA956HT, and PM2000) and three pipe sizes (1.5-in. [3.8-cm] Schedule 80, 1-in. [2.5-cm] Schedule 40, and 0.75-in. [1.9-cm] Schedule 40, respectively). Exhibit 2-2 illustrates the original position, size, and alloy type for the five uncooled tubes. At the request of UTRC, two of these uncooled alloy tubes were removed from the CAH tube bank following the September 1999 test and returned to UTRC for characterization. The tubes removed from the CAH represent the alloys designated Incoloy MA956HT and Incoloy MA956. Replacement tubes were fabricated using 1.5 in. (3.8 cm) Schedule 40 stainless steel pipe prior to a December 1999 test. No additional changes were made to the CAH this past quarter.

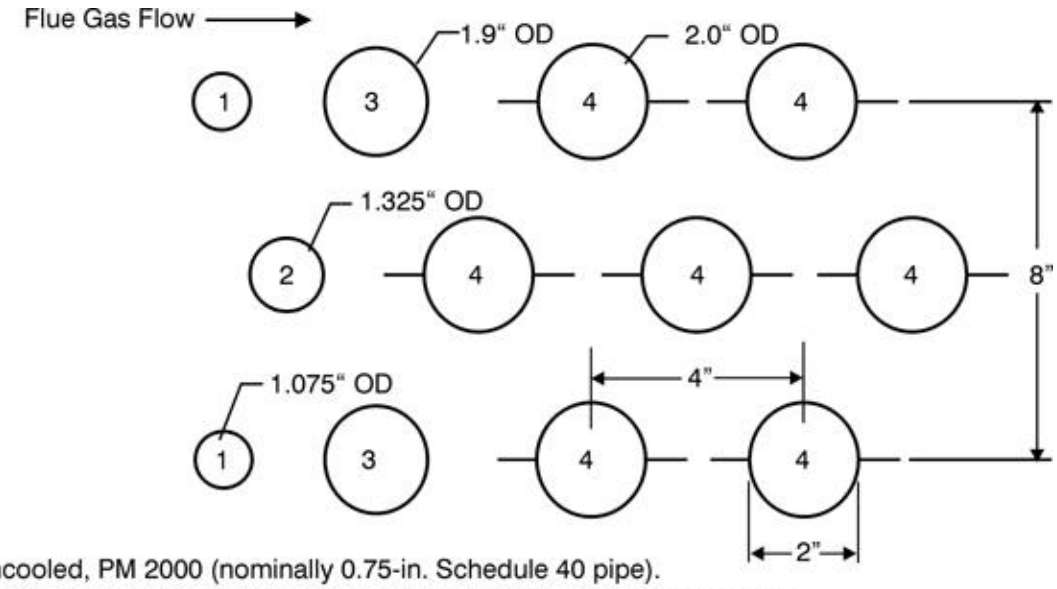

Exhibit 2-2 Illustration of the Tubes in the CAH Tube Bank Prior to a December 1999 SFS Test

Emission Control

A pulse-jet baghouse is used for final particulate control on the pilot-scale SFS. The baghouse design permits operation at both cold-side (250° to 400°F, 121° to 205°C) and hot-side (600° to 700°F, 316° to 371°C) temperatures. The primary baghouse chamber and ash hopper walls are electrically heated and insulated to provide adequate temperature control to minimize heat loss and avoid condensation problems

on start-up and shutdown. The main baghouse chamber was designed with internal angle iron supports to handle a negative static pressure of 20 in. W.C. (37 mm Hg).

During the past quarter, the tube sheet used permitted the installation of 36 bags arranged in a six-by-six array. Bag dimensions are nominally 6 in. (15.2 cm) in diameter by 10 ft (3.0 m) in length, providing a total filtration area of 565 ft^2 (52.5 m^2). The bag type being used at this time is a 22-oz/yd^2 (747-g/m^2) woven glass bag with a polytetrafluoroethylene (PTFE) membrane. Pulse cleaning of the bags was accomplished on-line in March using a reservoir pulse-air pressure of nominally 60 psig (4.1 bar). Baghouse performance observations during the March test are summarized later in this report.

Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, process air, process water, temperatures, static and differential pressures, and flow rates. The process control and data acquisition system is based on a Genesis software package and three personal computers. Two sets of flue gas instrumentation (oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen species) are dedicated to support the operation of the SFS. Flue gas is transferred from the sample point through a heated filter and sample line to the sample conditioner before it reaches the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse. Total flue gas flow rate through the SFS is measured using a venturi. No instrumentation work was completed this past quarter other than routine maintenance and calibration.

Pilot-Scale SFS Activities This Quarter

The pilot-scale SFS was fired on natural gas (heatup and cooldown) and a Cordero Rojo subbituminous coal for 200 hours during the period March 19–30 (SFS-RH12-0200). Because the results from the March test were not available for inclusion in the January through March quarterly report, they are presented here. The purpose of the test was to evaluate the Kyocera tile installed in early December, as well as the effectiveness of a sootblowing capability added to the CAH. Data evaluation and sample analysis have been completed. Therefore, this report summarizes the results and observations for the March test as well as SFS maintenance and modification activities this past quarter. In addition, a 200-hr bituminous coal-fired SFS test was completed in June. In comparison to earlier bituminous coal-fired tests, the June test was performed to evaluate the heat-transfer performance and slag corrosion resistance of a complete set of new Kyocera tiles, demonstrate an RAH panel exit air temperature of 2000°F (1094°C) for more than a few minutes, measure the performance of the CAH with finned tubes, and determine if CAH deposits can be cleaned by sootblowing. However, results from the June test are not available for inclusion in this report and will be summarized in a subsequent quarterly report.

The March 2000 SFS test was terminated after completion of 200 hr of a planned 200-hr coal-fired test. Coal firing was terminated, and natural gas firing was initiated and continued for 2 hr to maintain furnace operating temperature (2800°F/1538°C) and minimize the quantity of residual slag on the RAH tile surfaces and in the slag screen and slag tap. Normally, furnace temperature would be maintained for 4 hr while natural gas was fired. However, at the conclusion of the March test, 2 hr was considered adequate because the fluid temperature of the ash was much lower than the nominal operating temperature of the furnace and slag screen. After 2 hr of natural gas firing, stepwise reductions in the firing rate were made to control cooldown at a rate of <100°F/hr (38°C/hr). Natural gas firing was discontinued once the furnace temperature reached 1500°F (816°C). At that point, air flow rates were reduced to minimums, the SFS was allowed to cool slowly for a few days before the top section of the furnace was removed to permit

inspection of the RAH panel. Furnace inspection following the March test confirmed that 2 hr of natural gas firing was adequate to avoid slag accumulation on the RAH tiles.

Fuel Feed System

Nominal feed rates during the March test were 270° to 280 lb/hr (123° to 127 kg/hr). Adjustments to coal feed rate were made in order to maintain a flue gas temperature near the RAH tile surfaces and furnace exit of 2800EF (1538EC). Coal feed was continuous except for a 6-hr natural gas-fired period (roughly Run Hours 125 to 131) required to repair an electrical problem with the coal feeder and a 1.5-hr natural gas-fired period (Run Hour 143) required to clean out a plug in the slag tap. The slag pot below the slag tap was changed once during the March test as planned with no interruption of coal feed. Exhibit 2–3 illustrates the coal feed rate data for the March test. During the test, the coal feed rate was stable except for minor spikes (high and low) associated with coal-hopper refill cycles.

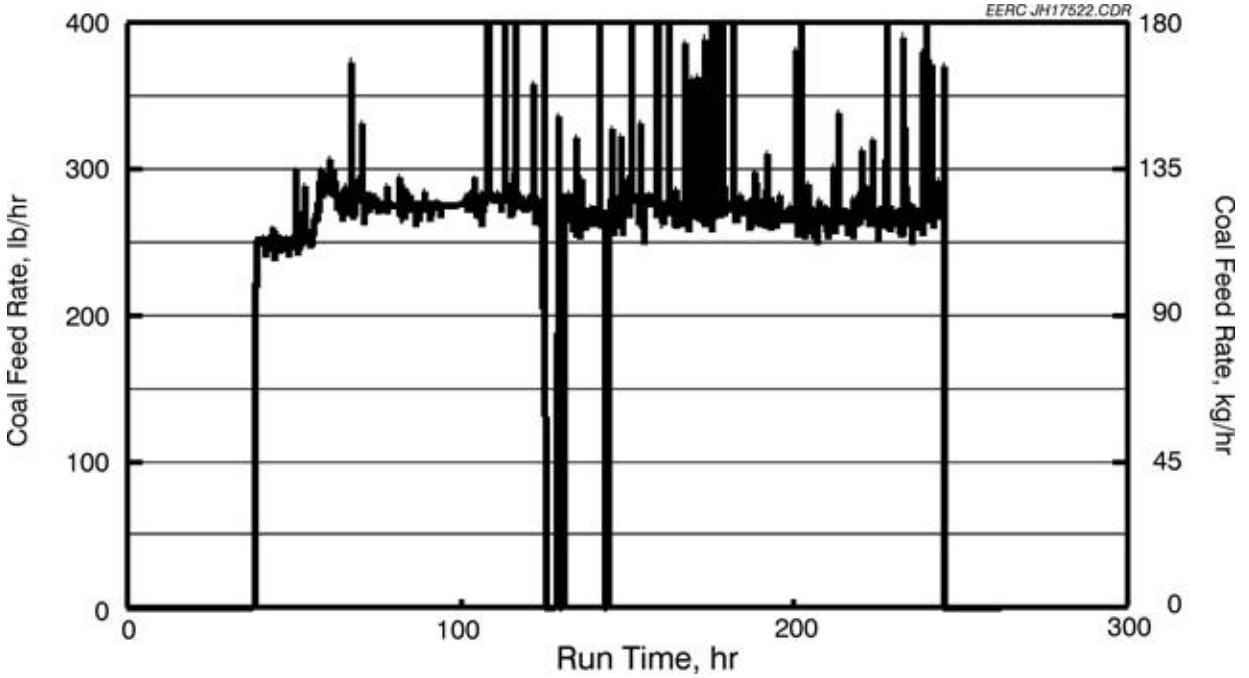

Exhibit 2-3 Coal Feed Rate Versus Run Time for the March Test, SFS-RH12-0200

Table 2-2 summarizes analytical results for all of the coals and lignites that have been fired in the SFS through March 2000. They include Illinois No. 6, eastern Kentucky, and Prater Creek bituminous coals, Rochelle and Cordero Rojo subbituminous coals, and Coal Creek Station (CCS) and Milton R. Young Station (MRYS) lignites. The analyses of the composite Cordero Rojo coal fired in March indicated that the as-fired fuel contained 25.3-26.1 wt% moisture, 5.3–5.4 wt% ash, and 0.45 wt% sulfur. The heating value was 8819–8853 Btu/lb (20,572–20,493 kJ/kg) on an as-fired basis. These data are similar to the Rochelle subbituminous coal previously fired. However, the Cordero Rojo subbituminous coal had slightly higher moisture, ash, and sulfur, resulting in a 2%–5% lower heating value. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2250°F (1233EC) and a fluid temperature of 2286EF (1253EC). The fluid temperature of the Cordero Rojo coal ash was within the range observed for the Rochelle subbituminous coal and 200° to 300°F (111° to 167EC) lower when compared to the analyses of the Illinois No. 6 fuel previously fired.

Dry-sieve analysis indicated that the pulverized Cordero Rojo coal was nominally 58–60 wt%–200 mesh (74 µm) in March. This is a larger size distribution than was observed for the bituminous coal fired in December 1999 and similar to that observed for bituminous fuels fired the second and third quarters of 1999. The desired size distribution was 70 wt% –200 mesh (74 µm). The larger size distribution observed in March may be the result of the higher fuel moisture content or an indication of a need for pulverizer maintenance or adjustments. In any case, the carbon content of the fly ash collected in the baghouse was 0.40 wt%, indicating good combustion efficiency during the March test.

X-ray fluorescence (XRF) analysis results for the various ashed fuels are summarized in Table 2-2 and reported as oxides. The Cordero Rojo coal ash was very similar to the Rochelle subbituminous coal ash previously characterized. The Cordero Rojo coal ash had slightly higher alumina, iron, and calcium and slightly lower magnesium and sodium than the Rochelle fuel. As expected, when compared to the bituminous coals, the Cordero Rojo coal ash contained significantly less silica, alumina, and iron and significantly more calcium and magnesium. The impacts of the lower ash fusion temperatures/properties on the performance of the slag screen and slag tap are discussed later in this report.

Table 2-2
Results of Fuel and Fuel Ash Analysis for Slagging Furnace Tests[1]

	Illinois No. 6 Bituminous Coal	Kentucky Bituminous Coal	Prater Creek Bituminous Coal	Rochelle Subbituminous Coal
Proximate Analysis, wt%				
Moisture	**2.8–10.3**	**2.3–2.5**	**2.0**	**21.6–24.3**
Volatile Matter	**35.9–39.9**	**38.2–38.7**	**38.7**	**35.6–37.4**
Fixed Carbon	**43.3–46.3**	**54.7–54.9**	**54.5**	**35.8–36.7**
Ash	**10.6–11.7**	**3.9–4.7**	**4.7**	**4.3–4.7**
Ultimate Analysis, wt%				
Hydrogen	**4.7–5.8**	**5.2–5.5**	**5.4**	**6.1–6.4**
Carbon	**61.6–67.6**	**77.5–78.2**	**78.3**	**53.0–55.2**
Nitrogen	**0.8–1.9**	**1.8**	**2.3**	**0.6–0.7**
Sulfur	**3.2–4.1**	**0.8–1.0**	**0.8**	**0.3**
Oxygen	**10.6–17.6**	**9.6–9.7**	**8.4**	**32.9–33.4**
Ash	**10.6–11.7**	**3.9–4.7**	**4.7**	**4.3–4.7**
Heating Value, Btu/lb	**11,015–11,658**	**13,861–14,120**	**14,167**	**9021–9328**
Percent as Oxides, wt%				
SiO_2	**49.3–53.9**	**42.5–44.8**	**38.4**	**26.7–27.1**
Al_2O_3	**19.8–21.5**	**28.9–29.8**	**25.0**	**15.5–16.3**
Fe_2O_3	**13.6–17.5**	**13.7–14.5**	**22.5**	**6.3–6.6**
TiO_2	**0.9–1.0**	**1.1**	**1.0**	**1.2–1.4**
P_2O_5	**0.1–0.2**	**0.1**	**0.1**	**0.7–0.9**
CaO	**2.6–3.6**	**1.9–2.8**	**3.8**	**21.6–24.3**
MgO	**1.5–2.0**	**2.2–2.4**	**2.1**	**6.7–6.9**
Na_2O	**1.1–1.5**	**1.1–1.3**	**0.3**	**1.5**
K_2O	**1.9–2.3**	**2.7–3.0**	**2.2**	**0.1–0.4**
SO_3	**2.5–4.0**	**2.4–3.8**	**4.6**	**15.6–17.0**
Ash Fusion Temp., °F				
Initial	**2315–2392**	**2398–2577**	**2483**	**2202–2295**
Softening	**2342–2418**	**2440–2603**	**2490**	**2205–2308**
Hemisphere	**2392–2448**	**2474–2621**	**2544**	**2214–2311**
Fluid	**2491–2593**	**2588–2684**	**2593**	**2221–2325**
Sieve Analysis				
Screen Mesh Size	**Weight Percent Retained**			
100	**1.8–25.2**	**8.1–11.4**	**13.6**	**7.6–8.8**
140	**0–14.9**	**12.9–13.9**	**15.1**	**14.2–15.4**
170	**0–14.9**	**NA[2]**	**NA**	**NA**
200	**9.6–13.5**	**11.4–13.5**	**12.4**	**14.3–14.4**
230	**0–16.2**	**8.7–9.4**	**8.3**	**8.4–9.1**
270	**0.5–14.6**	**0.7–1.6**	**0.8**	**2.0–5.6**
325	**7.4–14.7**	**11.9–12.7**	**10.9**	**4.8–11.6**
400	**0–4.7**	**NA**	**NA**	**NA**
Pan	**29.7–57.8**	**41.2–42.6**	**38.8**	**39.7–43.4**
Total %	**99–100.2**	**99.9–100.1**	**99.9**	**98.6–100.6**

[1] **Lignite analysis is presented on an as-fired basis.** [2] **Not available.** **Continued . . .**

Table 2-2 (continued)

	Cordero Rojo Subbituminous Coal	Coal Creek Station Lignite	Milton R. Young Station Lignite
Proximate Analysis, wt%			
Moisture	25.3–26.1	31.6–37.9	33.8–37.1
Volatile Matter	35.8–36.5	29.4–31.5	30.4–32.1
Fixed Carbon	32.7–32.9	26.4–26.8	26.9–27.9
Ash	5.3–5.4	6.3–10.2	5.6–6.2
Ultimate Analysis, wt%			
Hydrogen	6.3	6.4–6.8	7.0–7.2
Carbon	49.4–49.7	38.5–40.9	41.1–43.4
Nitrogen	1.2	0.6	0.6
Sulfur	0.45	0.5–0.7	0.7–0.9
Oxygen	37.1–37.2	41.1–47.3	42.1–44.9
Ash	5.3–5.4	6.3–10.2	5.6–6.2
Heating Value, Btu/lb	8818–8853	6300–6708	6933–7144
Percent as Oxides, wt%			
SiO_2	26.7–26.8	31.8–35.5	11.2
Al_2O_3	17.1–17.5	11.7–12.0	8.6
Fe_2O_3	6.8–7.2	6.4–8.0	13.2
TiO_2	1.6	0.5	0.2
P_2O_5	1.1	0.3	0.1
CaO	26.1–26.2	17.0–18.7	21.3
MgO	5.2	6.5–7.0	7.3
Na_2O	1.0	2.9–3.2	11.7
K_2O	0.3–0.4	1.3	0.2
SO_3	13.4–13.7	16.0–19.0	26.2
Ash Fusion Temp., °F			
Initial	2221	2170–2188	2370–2371
Softening	2250–2251	2181–2196	2381–2384
Hemisphere	2262–2266	2189–2203	2384–2387
Fluid	2286	2196–2219	2392–2428
Sieve Analysis			
Screen Mesh Size	**Weight Percent Retained**		
100	11.0–13.5	6.4–10.3	14.9
140	15.0–15.1	12.3–13.8	15.7
170	NA[2]	NA	4.6
200	13.3–14.2	11.9–12.3	8.5
230	8.0–9.0	3.7–8.5	NA
270	2.2–2.9	6.2–10.2	3.1
325	9.4–11.0	6.4–6.5	14.9
400	NA	NA	NA
Pan	37.6–38.0	41.5–48.2	38.2
Total %	100.0–100.2	98.3–99.9	99.9

[1] Lignite analysis is presented on an as-fired basis. [2] Not available.

Slagging Furnace Operation

The slagging furnace heating rate during the March test period was limited to 100°F/hr (56°C/hr) while natural gas was fired, as recommended for the RAH panel by UTRC. When the furnace reached normal operating temperature (2800°F, 1538°C), the main burner was switched from natural gas to coal firing. The coal-firing rate was nominally 2.4 to 2.5 MMBtu/hr (2.5 to 2.6 $\times$ 10^6 kJ/hr) with an auxiliary burner firing rate of 0.8 MMBtu/hr (0.84 $\times$ 10^6 kJ/hr). These coal-firing conditions were maintained for 200 hr in an attempt to maintain a furnace flue gas temperature near the RAH panel of 2800°F (1538°C). This temperature was established initially using two Type S thermocouple measurements and two optical pyrometer measurements. As thermocouple performance degraded with slag corrosion, furnace temperatures were measured using the two optical pyrometers and maintained with adjustments to the coal feed rate. A summary of furnace and slag screen temperatures is presented as a function of run time in Exhibit 2-4. Corresponding slagging furnace firing rate data are summarized in Exhibit 2-5.

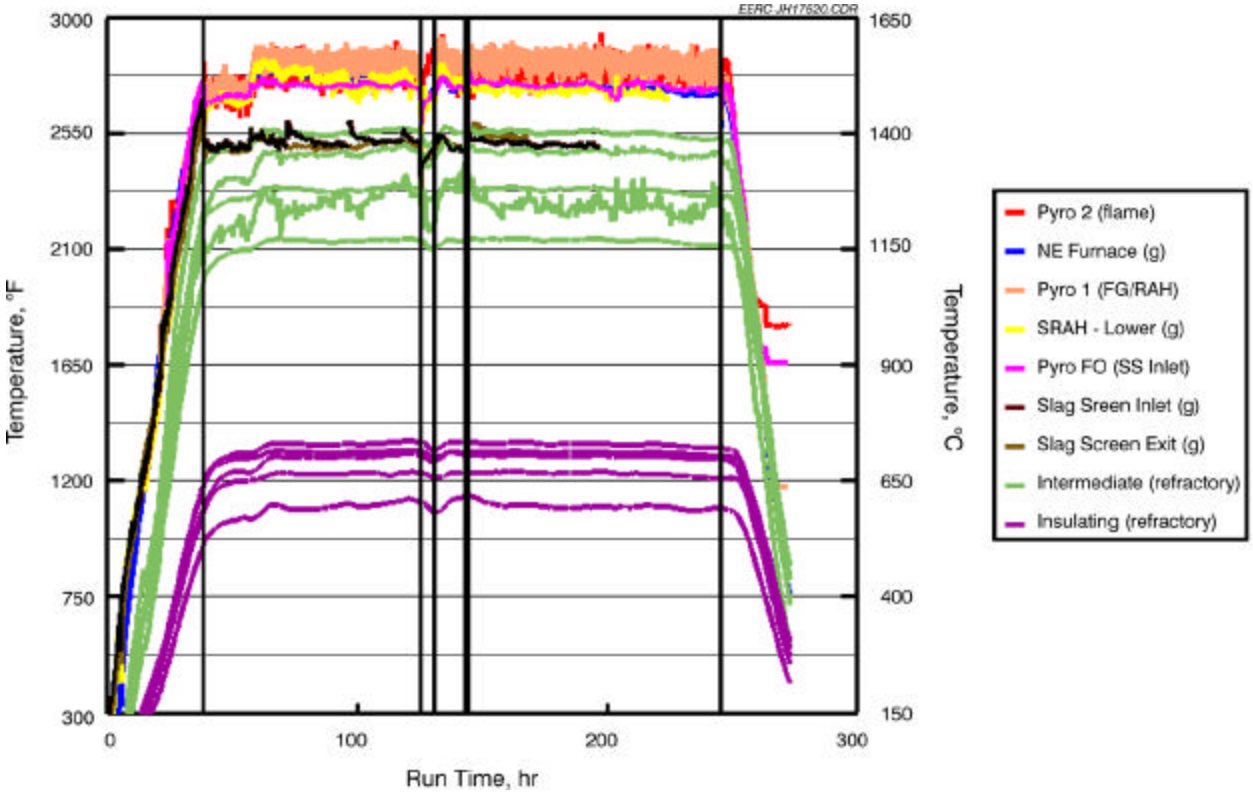

Exhibit 2-4 Furnace and Slag Screen Temperatures Versus Run Time for the March Test, SFS-RH12-0200

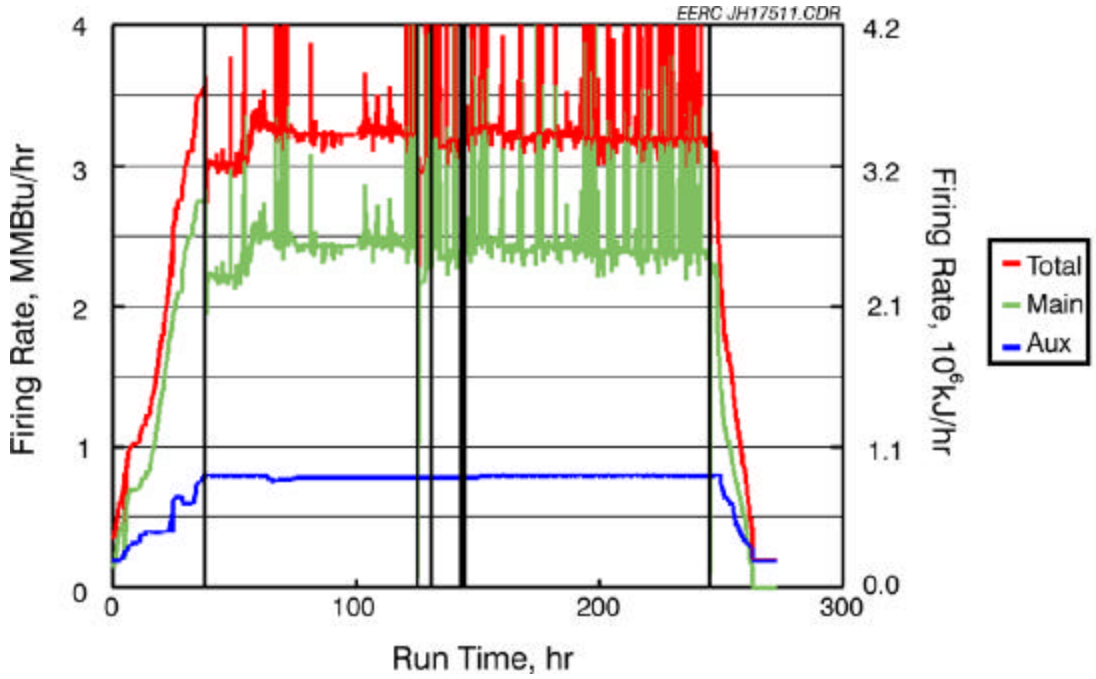

Exhibit 2-5 Slagging Furnace Firing Rate Versus Run Time for the March Test, SFS-RH12-0200

The total furnace-firing rate (main plus auxiliary burners) ranged from nominally 3.2 to 3.3 MMBtu/hr (3.4 to 3.5 × 10^6 kJ/hr). The main burner-firing rate ranged from 2.4 to 2.5 MMBtu/hr (2.5 to 2.6 × 10^6 kJ/hr), accounting for about 74%–76% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2800° to 2850°F (1538° to 1566°C). Measured furnace exit temperature typically matches the furnace wall temperature. However, during the March test, the furnace exit temperature was nominally 85°F (47°C) lower. The reason for this temperature difference is believed to be the development of a crack in the high-density refractory target for the optical pyrometer measuring furnace exit temperature. Development of the crack created a small area of heat loss affecting the optical pyrometer measurement. With replacement of the high-density refractory in the furnace exit, this problem appears to have been resolved.

Furnace refractory temperatures ranged from 1090° to 1355°F (588° to 735°C) for the hot side of the insulating refractory to as high as 2550°F (1399°C) for the cold side of the high-density refractory. Compared to the December 1999 test period firing Illinois No. 6 coal, the insulating refractory temperatures were 40° (36°C) lower, and high-density refractory temperatures were 65° to 80°F (36° to 44°C) lower. These lower refractory temperatures were observed even though the total furnace firing rate in March was 27% to 28% higher than the firing rate in December. In addition, the main burner firing rate in March was 20% higher than that required in December, 2.4 to 2.5 MMBtu/hr (2.5 to 2.6 × 10^6 kJ/hr) versus 2.0 to 2.1 MMBtu/hr (2.1 to 2.2 × 10^6 kJ/hr). However, the result was a 100°F (56°C) lower relative furnace flame temperature in March, nominally 2850°F (1566°C) versus 2950°F (1621°C). The lower furnace temperatures observed in March with a higher firing rate were the result of a higher fuel moisture content, nominally 26 wt% (Cordero Rojo subbituminous coal) in March versus 3 wt% (Illinois No. 6 bituminous coal) in December. A comparison of the March 2000 furnace temperatures with temperatures observed in March 1998, when the Rochelle subbituminous coal was fired, is not appropriate because in March 1998 both the small and large RAH panels were installed and the optical pyrometers were not available at that time.

The high-density refractory lining the furnace was found to be in good condition following the December 1999 test. However, following the subbituminous coal test in March 2000, the condition of the high-density refractory in the top and bottom sections of the slagging furnace had deteriorated to a point requiring replacement. In addition, replacement of the ceramic components in the RAH panel was planned prior to the next SFS test scheduled for June. Therefore, the EERC elected to replace the high-density refractory in all four furnace sections. Exhibit 2-6 presents a photograph of the interior of the furnace showing the RAH panel and the refractory damage surrounding the RAH panel following the March test. Although not obvious in the photograph, the high-density refractory liner in the furnace is continuing to darken with each coal-firing period. Slag tap performance was a problem when the Cordero Rojo subbituminous fuel was fired in March because of the corrosive nature of the slag and the resulting refractory damage observed in the bottom of the slagging furnace, the slag tap, and below the slag tap.

Exhibit 2-6 Photograph of Furnace Interior Following the March Test, SFS-RH12-0200

Main and Auxiliary Burners

The main and auxiliary burners performed well during the March test. As previously stated, the main burner swirl was maintained at about 20%, while the auxiliary burner swirl setting was 80%–100%. Carbon efficiency for the Cordero Rojo subbituminous coal was >99.95% because of the high furnace operating temperature and residence time. On the basis of operating experience, the EERC intends to continue minimum main burner swirl as necessary to establish a stable flame in order to maintain uniform temperatures over the length of the furnace and minimize NO_x emissions. Auxiliary burner firing is adjusted as necessary to maintain desired slag screen inlet temperatures, but will be minimized whenever possible.

Replacement of the primary air/fuel nozzle on the main burner was necessary following the March SFS test. This was done in conjunction with high-density refractory replacement in the furnace. Measurements show that roughly 4 in. of the nozzle has been lost (oxidized and eroded) since the burner was fabricated and originally installed in 1997. As a result of this effective shortening of the nozzle and the corrosive

character of the Cordero Rojo slag, some refractory damage was evident in the burner quarl following the March test. Inspection indicated that a similar repair was also necessary for the auxiliary burner.

Slag Screen

Although the slag screen was intact following the December 1999 test, the nine tubes were eroded/corroded to <50% of their original diameter. On the basis of previous experience, successful slag screen performance during the subbituminous coal-fired test planned for March required eighteen water-cooled tubes in the slag screen. Therefore, the slag screen was rebuilt in January 2000 allowing for the installation of eighteen water-cooled stainless steel tubes (six rows of three) covered with high-density alumina refractory resulting in an outside diameter of 1.5 in. (3.8 cm). The first row of tubes was fabricated using 0.5-in. (1.3-cm) stainless steel tubing, with the second and third rows fabricated using 0.38-in. (0.95-cm) stainless steel tubing. The remaining three rows of tubes were fabricated using 0.25-in. (0.64-cm) stainless steel tubing. The use of three different water-cooled tubing sizes was intended to maximize cooling to the rows most prone to erosion/corrosion and limit the potential for plugging in the slag screen.

The slag screen performed well during the subbituminous coal-fired test in March, and the tubes were found to be in fair condition. The first three rows of tubes, having the greatest degree of water cooling, were in reasonably good condition although erosion/corrosion of the tubes was evident. However, the last three rows of tubes with the least amount of cooling were in poor condition. On the basis of the condition of the last three rows of tubes following the March test, future tests with subbituminous coal or lignites would require the use of 0.38-in. (0.95-cm) stainless steel water-cooled tubes. Consideration would also be given to increasing the diameter of the water-cooled surfaces in the second and third rows as well. Measured slag screen flue gas temperatures during the March test were typically 2500° to 2550°F (1371° to 1399°C) at the inlet and 2475° to 2550°F (1358° to 1399°C) at the outlet. These measured temperatures are believed to be less than the actual flue gas temperatures because the thermocouples are located behind individual water-cooled slag screen tubes and because of observed thermocouple deterioration by slag attack. Therefore, slag screen temperature control is based on an optical pyrometer measurement at the furnace exit/slag screen inlet. The pyrometer temperature measurement showed that flue gas entering the slag screen was nominally 2800°F (1538°C). Slag screen operating temperature is selected on the basis of ash fusion data for the fuel to be fired. The EERC tries to operate the slag screen at flue gas temperatures of 100° to 200°F (56° to 112°C) above the fluid temperature of the fuel ash to ensure slag flow from the slag screen to the slag tap. The ash fluid temperature (under oxidizing conditions) of the composite samples of Cordero Rojo subbituminous coal analyzed following the March test period was determined to be 2286°F (1253°C). These data indicate that the slag screen could have been operated at a slightly lower temperature, 50° to 100°F (28° to 56°C), reducing slag erosion/corrosion in the furnace exit and slag screen without creating a slag plugging problem.

Slag screen plugging and differential pressure control problems were not encountered when Cordero Rojo coal was fired during the March test. An area immediately below the slag tap plugged several times during the March test, requiring a switch to natural gas firing once and occasional on-line cleaning. The apparent reason for the plugging observed in the vicinity of the slag tap was high-density refractory corrosion in the furnace exit, furnace bottom, and the slag tap itself. Slag tap temperature was controlled at 2550° to 2740°F (1232° to 1505°C) using the natural gas-fired tap burners. Temperature control was reasonably good for the first 150 hr of coal firing. However, during the last 50 hr of coal firing temperature control deteriorated as the slag tap deteriorated. The slag pot was changed once during the March test as planned because of slag accumulation. Ash fusion analysis of slag samples collected following the March

test determined that the fluid temperature of the slag (in an oxidizing environment) was 2477° to 2513°F (1359° to 1379°C). XRF analysis showed some enrichment of the silica and alumina concentration along with depletion of alkali components consistent with higher fluid temperature of the slag when compared to the coal ash. The increase in silica and alumina in the slag is also consistent with the refractory deterioration observed in the furnace exit and slag tap region.

Exhibit 2-7 contains photographs of the slag screen inlet (top) and outlet (bottom) following the March test. As previously stated, the greatest degree of erosion/corrosion was experienced by the last three rows of slag screen tubes.

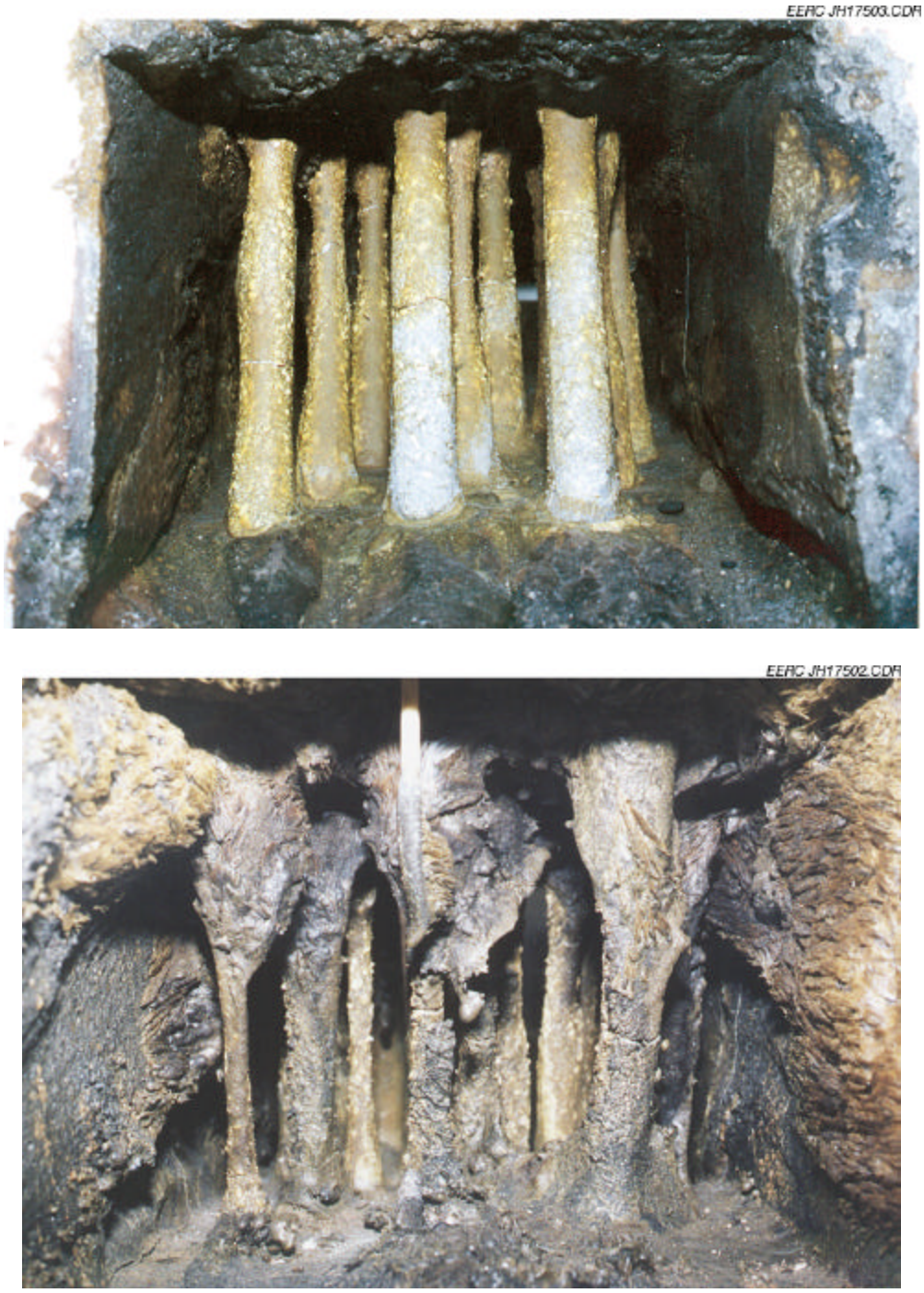

Exhibit 2-7 Photographs of the Slag Screen Inlet (top) and Outlet (bottom) Following the March Test, SFS-RH12-0200

Following the March test, slag and ash samples from system components and piping were collected and weighed in order to prepare a mass balance. A total theoretical ash quantity was calculated (2944 lb or 1337 kg) on the basis of the total coal fed and the measured ash content of the composite coal samples. Total slag and ash recovery from the March test was 83% (2439 lb or 1107 kg). Slag recovery from the furnace, slag pot, and dilution/quench zone represented 62% of the theoretical ash. Additional slag is evident on the furnace wall, on the RAH panel, at the bottom of the furnace, in the slag screen, and in the upper

section of the dilution/quench zone. However, this material is not recoverable from the high-density refractory.

Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represented 21% of the theoretical ash for the March test. Nominally 10% to 15% of the ash in the fuels fired in the SFS has been reaching the baghouse. In March, that value was 16% of the total ash/slag.

Dilution/Quench Zone

Slag deposits formed in the vicinity of the FGR nozzles during the March test. As a result, it was necessary to clean the area of the FGR nozzles on a periodic basis. The dilution/quench zone was initially cleaned after 30 hr of coal firing. During the March test, cleaning frequency (4–8 hr) after 30 hr of coal firing was dependent on relative heat transfer through the waterwall and flue gas recirculation flow rates rather than differential pressure in the quench zone. About 10% of the ash/slag recovered from the SFS was recovered in the dilution/quench zone. This quantity of material is smaller when compared to the Rochelle subbituminous coal test and recent bituminous coal tests. The smaller quantity of slag/ash collected in the dilution/quench zone during the March test is a direct result of improved slag screen performance. When compared to the Rochelle subbituminous coal test, the improvement is the result of more efficient tube cooling and reduced slag screen tube erosion/corrosion. When compared to recent bituminous coal-fired tests, the improvement is the result of an increase in the number of slag screen tubes from nine to eighteen. Experience to date has demonstrated that when Illinois No. 6 bituminous coal, subbituminous coals, and lignites are fired, the slag screen performs best when using 18 tubes (six rows of three). In addition, greater cooling is required when the subbituminous coals and lignite are fired to avoid significant tube erosion/corrosion. When low-ash, high-ash-fusion coals like the eastern Kentucky fuels are fired, 9 tubes (three rows of three) are adequate. Downstream of the FGR nozzles, the small quantity of ash observed on the refractory walls was weakly sintered.

During the SFS test in March, it was not necessary to inject calcium oxide into the flue gas just upstream of the pulse-jet baghouse to eliminate the sulfur trioxide entering the FGR piping and fan. The low sulfur content of the fuel and the calcium oxide content of the coal ash in this case were expected to limit sulfur trioxide concentration downstream of the baghouse. FGR piping and fan inspection following the March test confirmed that acid condensation had not occurred.

Process Air Preheaters

The process air for the CAH tube bank and the RAH panel is preheated using tube bundles downstream of the CAH. Further heating of the process air entering the RAH panel is achieved electrically. Process air for the CAH tube bank is supplied by the first process air preheater tube bundle. During the March test, process air entering the CAH tube bank was controlled at a set point of 1090°F (588°C) for nominal process air flow rates of 100 to 110 scfm (2.8 to 3.1 m^3/min). Process air temperatures at the exits of the other four preheater tube bundles were

nominally 1205° to 1310°F (652°to 710°C) for combined flow rates totaling 150 to 200 scfm (4.2 to 5.7 m^3/min).

Process air preheater temperatures are shown as a function of run time in Exhibit 2-8. The temperature data indicate that the process air preheater heat-transfer rate did not degrade significantly with time as ash deposits developed on the tube surfaces. As a result, process air temperature and flow rate were adequate to support operation of the CAH tube bank and RAH panel.

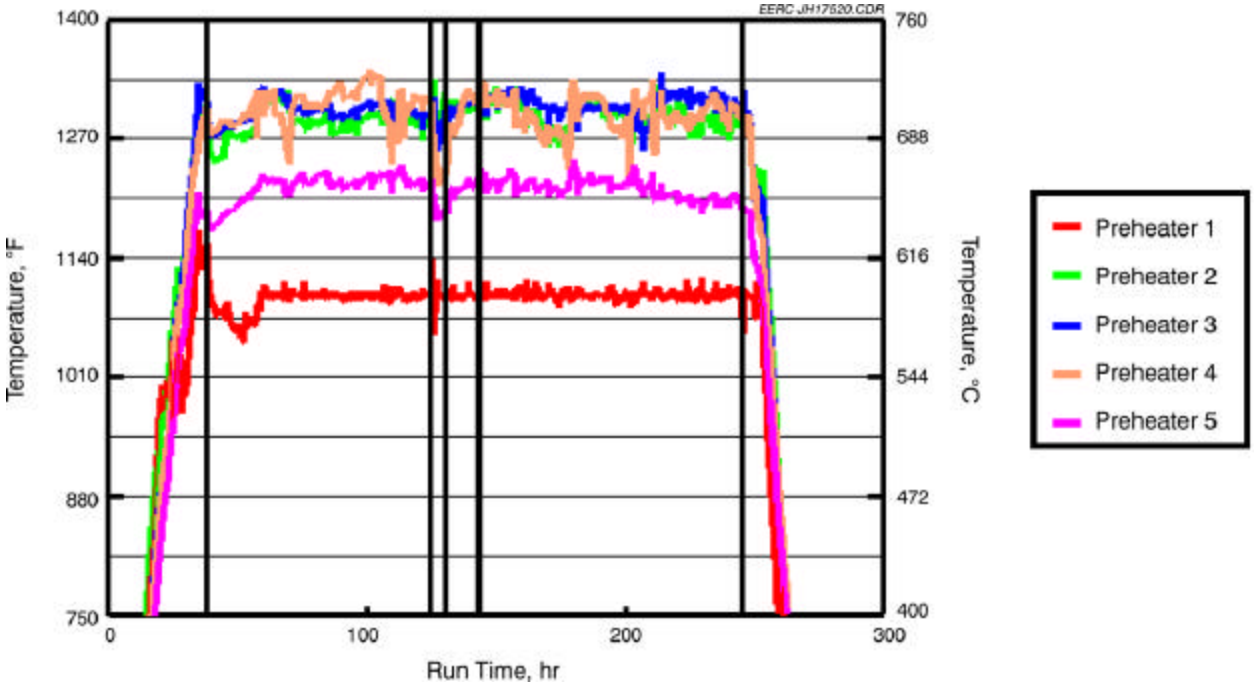

Exhibit 2-8 Process Air Preheater Temperatures Versus Run Time for the March Test, SFS-RH12-0200

Emission Control

During gas- and coal-fired furnace operation in March, baghouse temperatures and temperature profiles were nominal, and the electrical heaters worked well, limiting the potential for condensation on start-up and shutdown. Baghouse temperature ranged from 330° to 340°F (166° to 171°C). Flue gas flow rates were 935 to 1015 scfm (26.5 to 28.7 m^3/min). Actual flue gas flow rates through the baghouse were 1475 to 1620 acfm (41.8 to 45.9 m^3/min).

The 36 bags (total filtration area of 565 ft^2 [52.5 m^2]) used in the baghouse this past quarter were a 22-oz/yd^2 (747-g/m^2) woven glass with a PTFE membrane. The filter face velocities when the Cordero Rojo subbituminous coal was fired were 2.6 to 2.9 ft/min (0.79 to 0.88 m/min). These filter face velocities are low compared to conventional pulse-jet filtration systems typically operating at or near 4 ft/min (1.2 m/min). However, a detailed evaluation of baghouse performance has not been a specific objective within the scope of work to date.

Measured inlet and outlet particulate mass loadings ranged from 0.1553 to 0.2067 gr/scf (355.6 to 473.4 mg/Nm^3) and 0.0004 to 0.0008 gr/scf (0.9160 to 1.8321 mg/Nm^3), respectively, resulting in particulate collection efficiencies of 99.6% to 99.8% in March. A comparison of mass loading data from the March 2000 SFS test with a subbituminous coal-fired test completed in March 1998 is not possible

because particulate sampling was not completed in March 1998 as a result of budgetary constraints. Particulate mass loadings measured at the inlet to the pulse-jet baghouse are influenced by the coal firing rate, coal ash content, and the performance of the slag screen. Particulate mass loadings measured at the outlet of the pulse-jet baghouse are influenced by the filter media used, the inlet mass loading and particle size, and the concentration of sulfur trioxide in the flue gas. In general, the particulate mass loading data observed for the March SFS are consistent with expectations based on the fuel characteristics, fuel firing rate, and SFS operational experience. The variability or range of the inlet mass loadings is believed to be the direct result of some variation in fuel feed rate and ash content as well as some deterioration in slag screen performance as a result of slag erosion/corrosion of slag screen tubes. Since outlet mass loadings decreased with each of the first three sets of samples collected, it would appear that the variability of the outlet mass loadings was a function of bag conditioning with respect to ash characteristics and cleaning cycle performance.

Calculated particulate emissions from the pulse-jet baghouse ranged from 0.0014 to 0.0028 lb/MMBtu. The low end of the range represents the last two sampling periods completed, with the high end of the range representing the first sampling period. Although the range in measured particulate emissions represents a factor of 2, the data are generally comparable to emission rates previously measured when other coals and lignite (0.0004 to 0.0074 lb/MMBtu) were fired in the SFS. Sulfur trioxide concentration measurements were not made downstream of the pulse-jet baghouse in March because of the low fuel sulfur content and high alkali content of the fuel ash.

In addition to the standard EPA Method 5 sampling completed in March, respirable mass emissions (defined below) were measured at the outlet of the pulse-jet baghouse using a TSI Inc. aerodynamic particle sizer (APS-33). This real-time measurement method measures particle mass in the range of 0.5 to 15 μm. The primary advantages of this system are the high spatial resolution and the short sampling time. In the APS-33, particle-laden air is passed through a thin-walled orifice, with the particles lagging behind the gas because of their higher inertia. This lag allows the determination of the aerodynamic diameter of a particle by measuring its velocity as it exits from the orifice. To measure the particle velocity, the APS-33 employs a laser beam split in two and refocused onto two rectangular planes a set distance apart in front of the orifice. The light scattered by a particle passing through these beams is collected and focused onto a photomultiplier tube, which emits two pulses separated by the time taken for the particle to cross the distance between the two planes. This time interval is measured electronically and used to calculate the particle's aerodynamic diameter.

Respirable mass is a calculated value defined by the American Council of Governmental and Industrial Hygienists for particles in the aerodynamic size range of 2 to <10 μm. Exhibit 2-9 presents the respirable mass emissions data for the March test period. The data are presented on a mg/m^3 basis versus sampling time. The respirable mass emission rate was nominally 0.095 mg/m^3 based on an integrated average. Emission spikes as a function of cleaning cycles were similar, with spikes generally approaching 0.1 mg/m^3 and one cleaning cycle spike marginally exceeding 0.1 mg/m^3. When compared to previous respirable mass data resulting from various fuel types (bituminous coals and lignites), these data indicate an emission rate more than an order-of-magnitude higher than previously observed. EERC personnel familiar with the sampling methodology and equipment believe that the data are in error as a result of a high vacuum static pressure condition (>15 in. W.C./>28 mm Hg) at the sampling point during the March test. The reason for the high vacuum static pressure condition was the high flue gas flow rate through the SFS, the resulting

system differential pressure, and the required operating speed of the ID fan to maintain desired furnace static pressure.

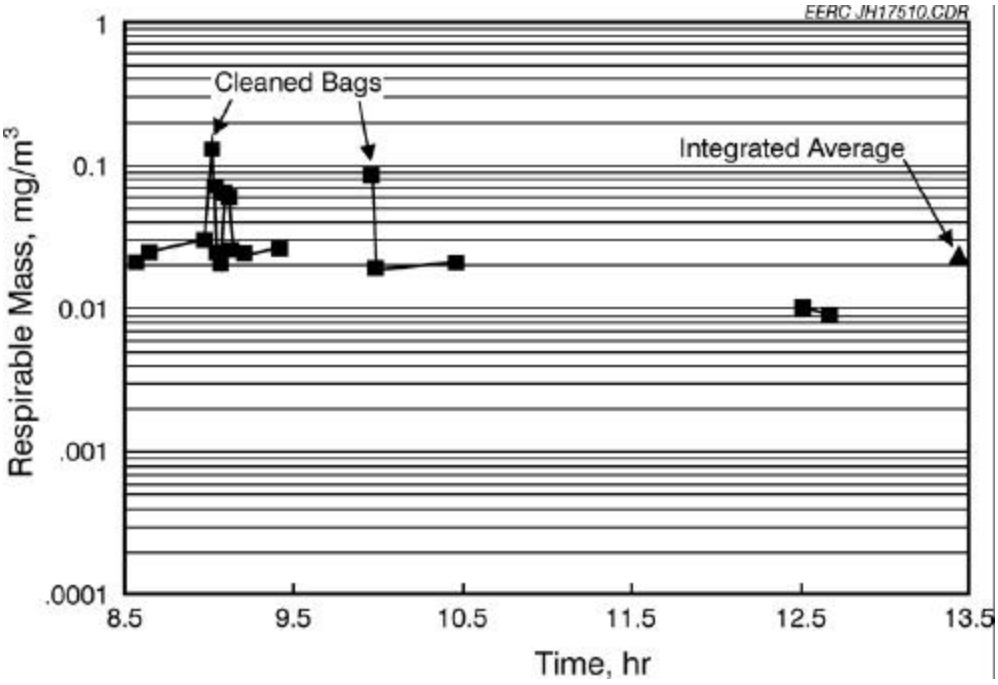

Exhibit 2-9 Respirable Mass Emissions Data for the March Test

Particle-size analysis was completed for two composite ash samples collected from the baghouse hopper for the March test. The data show the ash to be 100 wt% <8–10 µm, 80 wt% <5–6 µm, and 50 wt% <3–4 µm for the Cordero Rojo subbituminous coal. These values indicate an ash particle size less than those observed when bituminous coal was fired consistent with ash chemistry and particle formation mechanisms involving alkali vaporization and condensation.

Multicyclone sampling data indicated a very different particle-size distribution, 40–60 wt% <8.5 µm for the Cordero Rojo coal-fired SFS test. This inconsistency is yet to be explained and will be investigated further. Similar inconsistencies have been previously observed when multicyclone particle size data were compared to bulk ash analyses for samples resulting from the firing of bituminous coal and lignite.

Carbon content of the baghouse ash was measured to determine combustion efficiency. The carbon content was 0.40 wt% for the March test, comparable to other SFS tests but somewhat higher than the 0.10 wt% carbon value observed in December 1999. This difference is believed to result from a slightly larger fuel particle size in March, 58–60 wt% –200 mesh (74 µm) versus 74–77 wt% –200 mesh (74 µm) observed in December 1999 when an Illinois No. 6 bituminous coal was fired. The difference indicates a change in the pulverizer performance efficiency. Whether this change was caused by the higher moisture content of the subbituminous coal or the degradation of pulverizer hammers and/or screens is unknown at this time but will be investigated.

Pulse cleaning of the bags was accomplished on-line using a reservoir pulse-air pressure of nominally 60 psig (4.2 bar). The baghouse differential pressure cleaning set point was initially 5 in. W.C. (9 mm Hg). However, after 100 hr of coal firing, on-line cleaning was occurring on a 50-minute interval, and the differential pressure after cleaning was >3 in. W.C. (>6 mm Hg). The cleaning cycle set point was increased to 6 in. W.C. (11 mm Hg), and the on-line cleaning frequency was reduced to nearly a 2-hr cycle. The

differential pressure after cleaning was <4 in. W.C. (<7 mm Hg). However, it was occasionally necessary to manually trigger the cleaning cycle two or three times in order to achieve adequate bag cleaning.

Table 2-3 shows the average flue gas composition measured during the March test. The O_2, CO, and CO_2 data are based on furnace exit measurements made in the slag screen outlet. The CO concentrations in the slag screen were nominally 10 to 80 ppm during the March test. These values are lower than those observed for bituminous coals and are probably an indication of relative fuel volatility. The CO concentration measured in the slag screen indicates that some combustion was taking place in the slag screen and most likely in the dilution/quench zone and CAH section as well. This observation may be influenced by the auxiliary burner firing characteristics but, more likely, by the firing characteristics of the Cordero Rojo subbituminous coal fired in March. CO was not observed at the baghouse outlet sampling location unless the slag tap burners were operated at substoichiometric conditions, indicating that any CO observed in the slag screen was oxidized in the dilution/quench zone and CAH section.

NO_x concentrations in the flue gas ranged from 405 to 660 ppm at the exit of the baghouse. Total NO_x emissions (reported as nitrogen dioxide) were determined to range from 0.64 to

Table 2-3
Slag Screen Flue Gas Composition for the Cordero Rojo Coal-Fired SFS Test

	Concentration	lb/MMBtu
O_2	3.0%–5.8%	–
CO_2	12.6%–14.6%	–
CO	10–80 ppm	–
NO_x	455–605 ppm	0.64–1.18
SO_2	210–320 ppm	0.7–0.9

1.18 lb/MMBtu. Within the range reported, NO_x emissions were stable during the March test. Also, NO_x emissions were marginally lower in March when compared to the Illinois No. 6 coal-fired test in December 1999. This observation is consistent with the higher moisture content of the Cordero Rojo coal (nominally 25 wt%) and its lower furnace flame temperature when compared to the Illinois No. 6 coal (3–5 wt%) fired in December. The auxiliary burner firing condition is also believed to have affected the NO_x concentrations and emissions; however, no specific tests have been conducted to document the effect of the auxiliary burner on NO_x emissions.

No attempt at controlling sulfur emissions was made. Calculated maximum theoretical sulfur dioxide emissions were 2.4 to 2.6 lb/hr (1.1 to 1.2 kg/hr) or 1.0 lb/MMBtu for the Cordero Rojo subbituminous coal. These rates are based on the main burner firing rate and the sulfur content and heating value of the fuel. The sulfur dioxide emissions, calculated on the basis of measured sulfur dioxide in the flue gas, flue gas flow rate, and the coal firing rate, resulted in values ranging from 0.7 to 0.9 lb/MMBtu. The most likely explanation for the difference in calculated sulfur dioxide emission rates, 0.7–0.9 versus 1.0 lb/MMBtu, is that the alkali constituents in the fly ash reacted with sulfur dioxide in the flue gas, effectively reducing sulfur dioxide emissions.

Testing of the CAH Tube Bank

Exhibits 2-10 through 2-12 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the March test. Exhibit 2-13 illustrates the location of thermocouples in the CAH tube bank, and Table 2-4 presents a list of thermocouple descriptions.

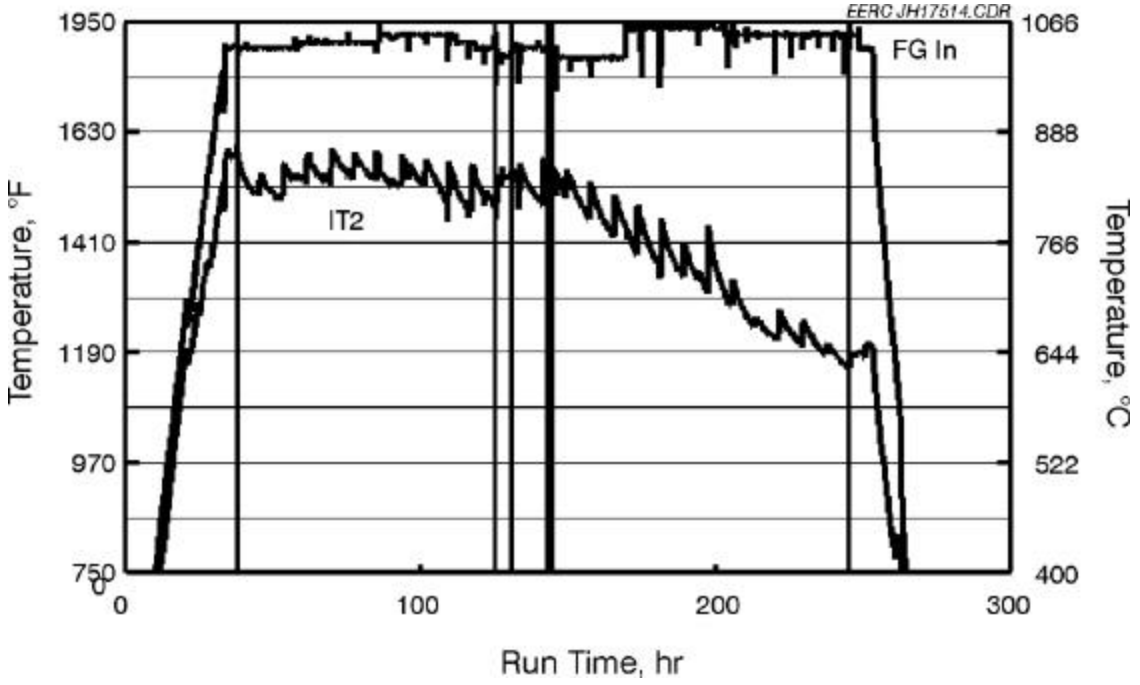

Exhibit 2-10 CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the March Test, SFS-RH12-0200 37

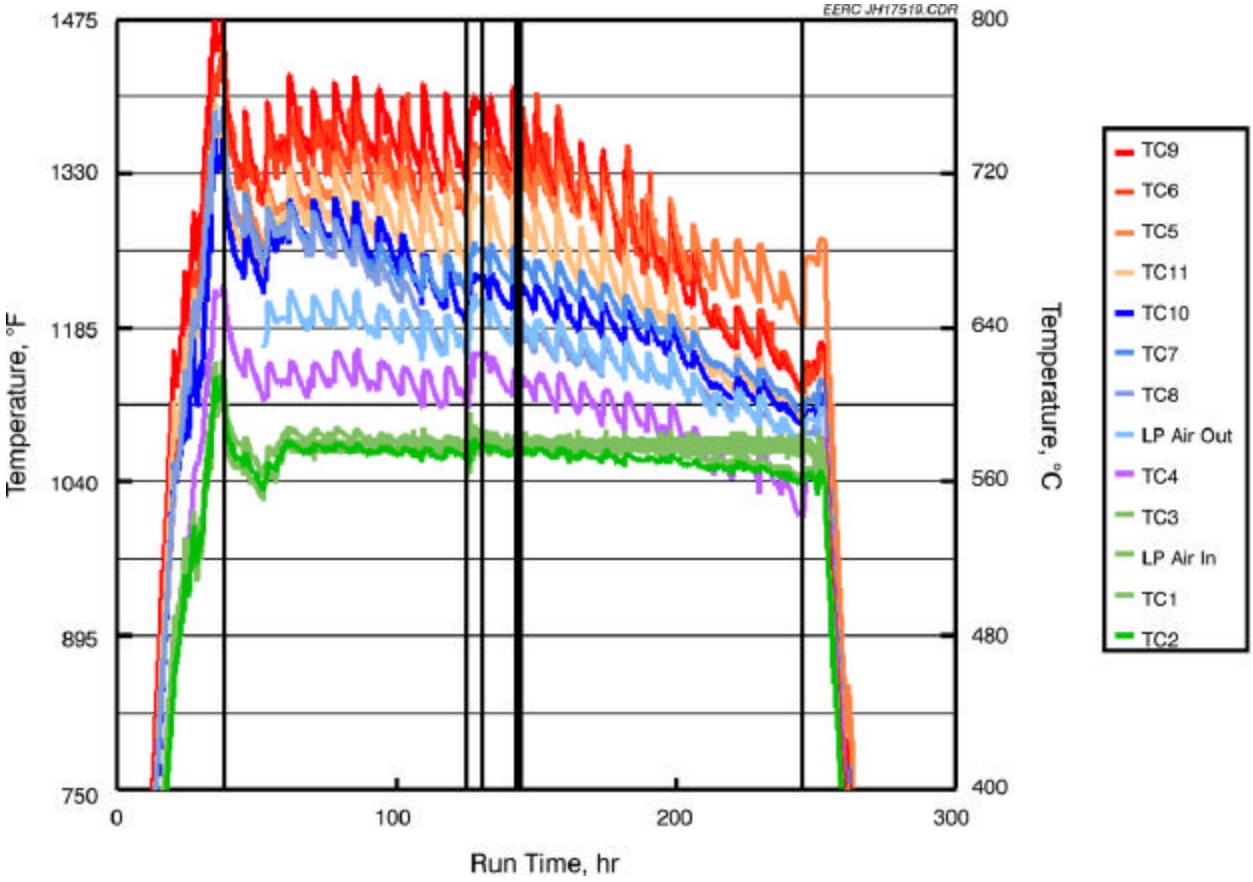

Exhibit 2-11 CAH Process Air Temperatures Versus Run Time for the March Test, SFS-RH12-0200

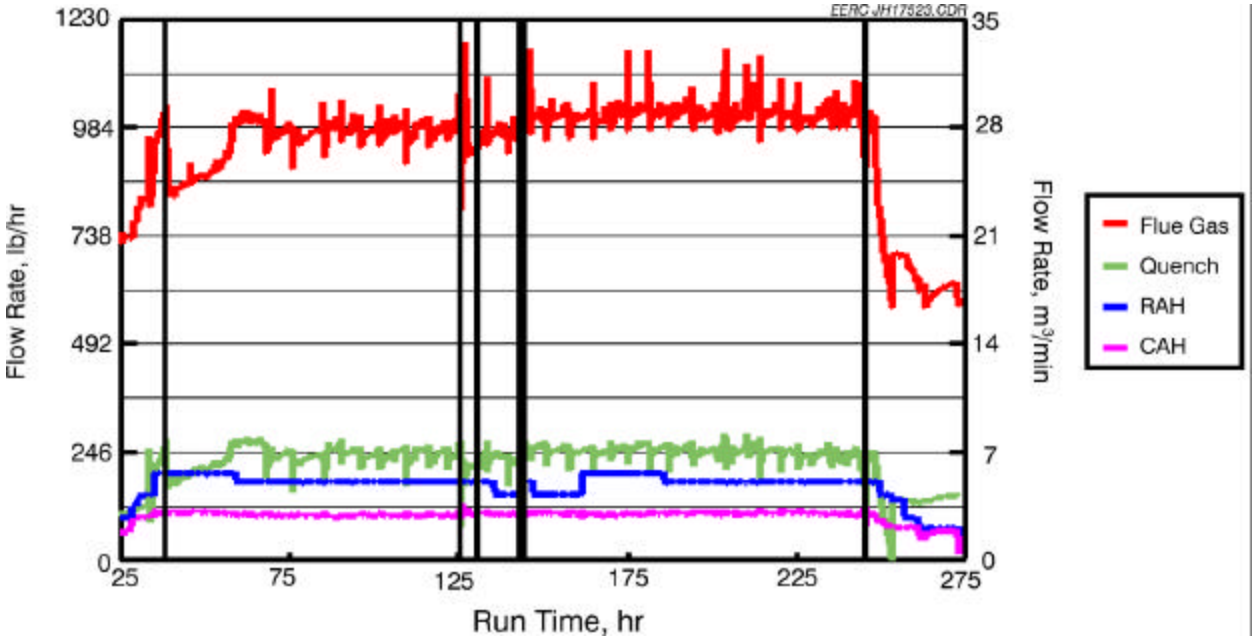

Exhibit 2-12 CAH Process Air, RAH Process Air, Quench Gas, and Flue Gas Flow Rates vs. Run Time for the March Test, SFS-RH12-0200

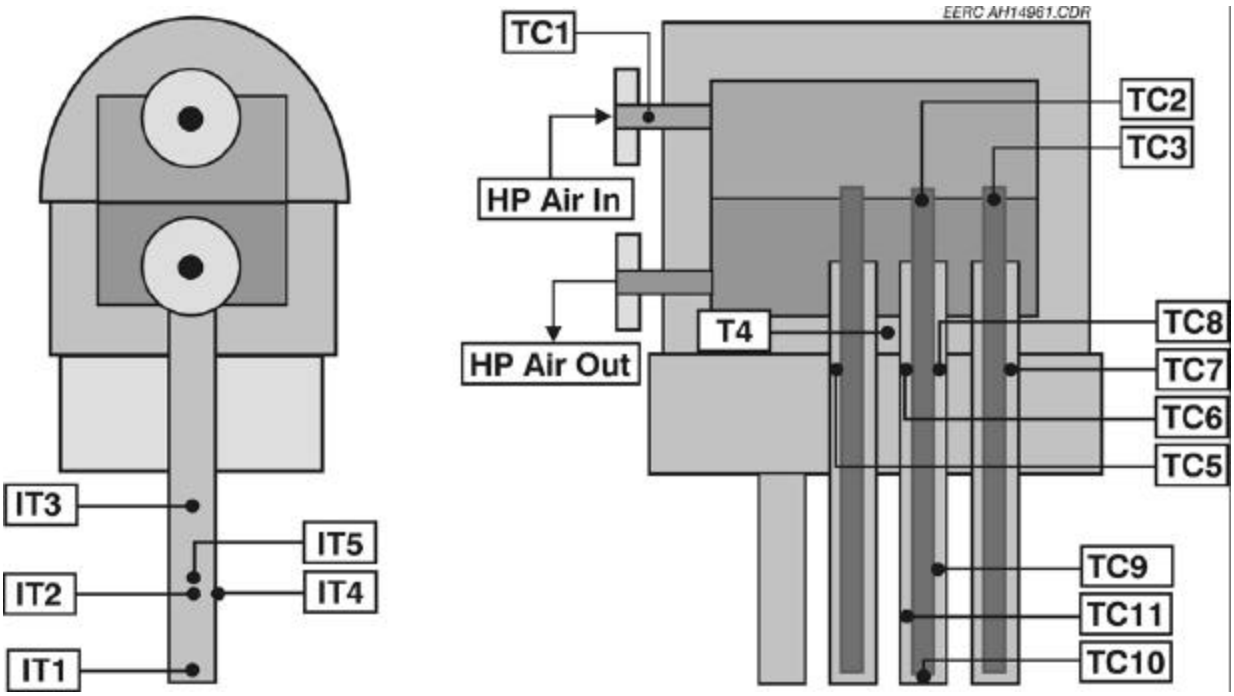

Exhibit 2-13 Thermocouple Locations in the CAH Tube Bank

Prior to an August 1998 test, all of the CAH thermocouples were replaced or repaired in conjunction with the installation of fins on the air-cooled tubes. However, one tube surface thermocouple (CAHIT3) was damaged when the tube bank was installed in the flue gas duct. One additional CAH thermocouple failed during both the August and December 1998 tests, and a fourth thermocouple failed at the beginning of a January 1999 test. Therefore, during the March test, only one of the five surface thermocouples was functioning properly. There are no plans to replace these thermocouples at this time because of the time and expense that would be required.

On the basis of a single thermocouple measurement, the clean tube surface temperatures were nominally 1580°F (860°C). During the March SFS test the EERC began sootblowing after 8 hr of coal firing and then repeated sootblowing every 8 hr for the duration of the test. The components of the sootblowing system used in March 2000 remained the same as those used in December 1999 as did the media (nitrogen gas) and media pressure (200 psig/13.8 bar) and flow rate (188 scfm/3.1 m^3/min). The approach simply involved the manual insertion and removal of a probe through an access port to the tube bank. This approach permits sootblowing between two rows of tubes. The duration of an actual sootblowing event did not exceed 15 s.

As a result of the sootblowing approach employed, the surface temperature remained relatively stable in the range of 1470° to 1580°F (799° to 860°C) during the first 100 hr of coal firing. However, after a short natural gas-fired period to repair the coal feeder, the tube surface temperature gradually decreased to 1160°F (627°C) over the final 100 hr of coal firing. This

Table 2-4
Description of CAH Thermocouple Locations[1]

Category	Label	Description
Air Inlet	CAHTC1	Bulk flow entering the inlet header
	CAHTC2	Air entering center tube
	CAHTC3	Air entering most downstream tube
Air Outlet	CAHTC6	Air leaving center tube
	CAHTC7	Air leaving most downstream tube
	CAHTC5	Air leaving most upstream tube
	CAHTC8	Air leaving side tube
Air in Active Region	CAHTC10	Bottom of center tube
	CAHTC11	4 in. up outside annulus, center tube
	CAHTC9	8 in. up outside annulus, center tube
Tube Surface	CAHIT1	1 in. up center tube, facing upstream (failed)
	CAHIT2	5 in. up center tube, facing upstream
	1 CAHIT3	8 in. up center tube, facing upstream (failed)
	1 CAHIT4	5 in. up center tube, facing to side (failed)
	1 CAHIT5	5 in. up center tube, facing downstream (failed)
Header Shell	CAHTC4	Next to shell on outside, between return air

[1] Thermocouple locations are illustrated in Exhibit 2-13.

decrease occurred even though sootblowing was repeated every 8 hr. Process air flow rate adjustments were limited during the March test resulting in flow rates of 100–110 scfm (2.8–3.1 m^3/min). Attempts to sootblow the CAH tube bank are evident as step increases in the tube surface and air temperature data as well the heat recovery data. A hypothesis is not available at this time to explain why the sootblowing approach was initially effective in controlling tube surface temperature but became less effective after 100 hr of coal firing.

While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 38,000 Btu/hr (40,090 kJ/hr) in March, comparable to previous SFS tests. The process air flow rate was 110 scfm (3.1 m^3/min). The inlet process air temperature was 1110°F (599°C), outlet process air was 1310°F (710°C), and flue gas was 1800°F (982°C) entering the CAH tube bank. Exhibit 2-14 presents heat recovery in the CAH as a function of run time.

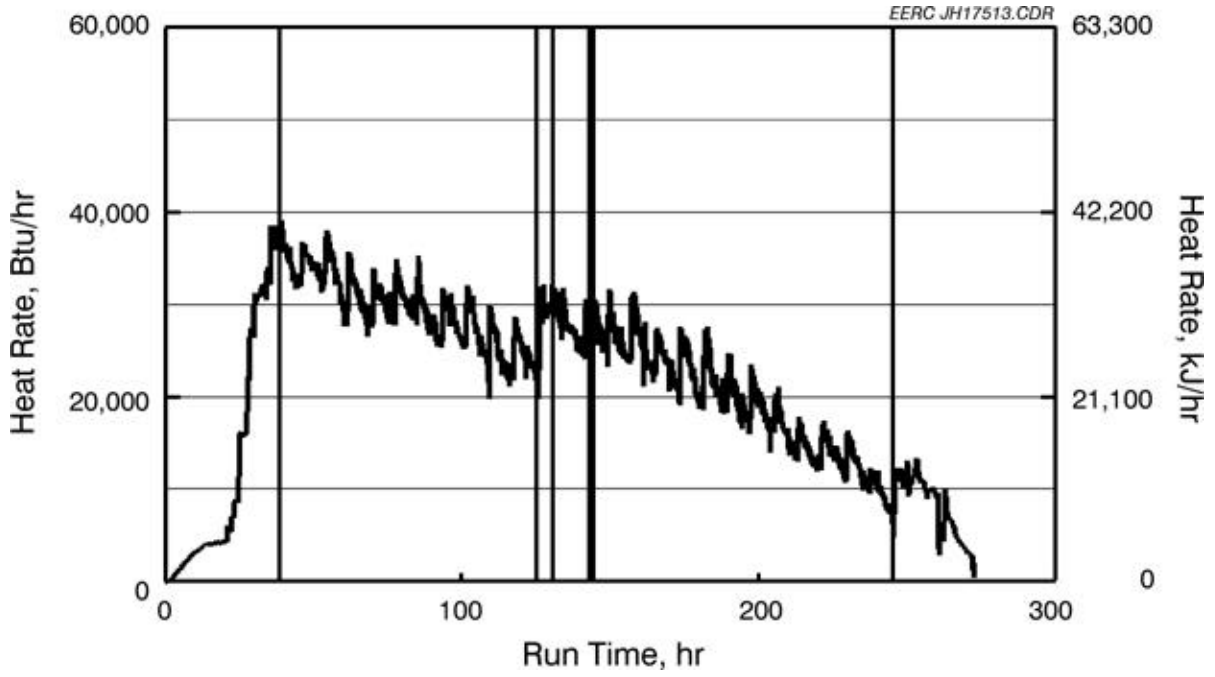

Exhibit 2-14 CAH Heat Recovery Versus Run Time for the March Test, SFS-RH12-0200

Once coal firing was stabilized, CAH heat recovery was initially 36,150 Btu/hr (38,138 kJ/hr) and decreased as ash deposits developed on the surface of the tubes. After 8 hr of coal firing CAH heat recovery had decreased to 32,115 Btu/hr (33,881 kJ/hr), and sootblowing was attempted. This first attempt to sootblow the CAH tubes effectively restored heat recovery. CAH heat recovery was effectively controlled in this range for roughly 50 hr or six sootblowing cycles before heat recovery began to degrade over a 24-hr period. An increase in the flue gas recirculation rate in the dilution/quench zone and total flue gas flow rate through the CAH tube bank stabilized heat recovery for about 24 hr. However, during the last 100 hr of coal firing, CAH heat recovery continued to degrade, consistent with the tube surface temperature observed. Although each sootblowing event resulted in an increase in tube surface temperature and heat recovery, after 200 hr of coal firing, heat recovery in the CAH degraded to nominally 10,000 Btu/hr (10,550 kJ/hr). The overall degradation of CAH heat recovery during the March test indicates that the sootblowing approach employed was not adequate. The data in

Exhibit 2-14 indicated that more frequent sootblowing should improve CAH heat recovery, but there is no guarantee that the degradation in heat recovery observed in March would not recur. Sootblowing every 4 hr when a subbituminous coal is fired should be attempted in the future if the opportunity occurs. Improved sootblowing effectiveness may require a modification to the methodology employed to increase the tube surface area affected by each sootblowing event.

No attempt had been made previously to sootblow the CAH tubes prior to the installation of fins. Therefore, conclusions cannot be drawn concerning the potential advantages of the fins when routine sootblowing is effectively used to maintain desired CAH heat recovery. Also, the presence of the fins may actually inhibit the effectiveness of sootblowing.

Previous data support the conclusion that the addition of the fins to the air-cooled tubes improves heat recovery during the coal-fired test periods. The fins appear to reduce the rate of heat-transfer degradation as ash deposits develop and help to maintain a higher heat-transfer rate once the deposits have formed.

However, no improvement in heat recovery was observed during the initial natural gas-fired periods with clean tube surfaces.

Because of the attempts to sootblow the CAH tube bank during the March test and previous characterization of CAH ash deposits resulting from a subbituminous coal-fired test, CAH ash deposits were not collected for characterization following the test. The deposits that formed were generally limited to the leading and trailing edges of the tubes. Exhibit 2-15 presents photographs of ash deposits on the surface of the tubes following the March test. The top photograph shows three uncooled tubes that were free of ash deposits as a result of sootblowing efforts. The sidewall of one air-cooled tube is partially visible, indicating a degree of sootblowing effectiveness. The bottom photograph shows an uncooled tube with a clean trailing edge as well as two air-cooled finned tubes with roughly one-third of their surfaces cleaned to a degree. These photographs support the observed need for greater sootblower coverage. Substantial leading- and trailing-edge deposits are visible in both photographs. However, CAH tube bank plugging was not a problem. No deposits were observed bridging the flue gas path between the tubes.

Deposit strength is a function of ash chemistry, particle size, and temperature history. The relative strength of the deposits is indicated by the fact that the deposits remained intact when the tube bank was removed from the duct. This observation is consistent with results from previous tests with other fuel types. However, a direct comparison with a previous subbituminous coal-fired test is not possible because of differences in test duration and the presence of fins on the CAH tubes during the March test. The total weight of the deposits collected from the CAH tubes and duct was 55 lb (25 kg). The total weight of the deposits collected from the CAH tubes was 21 lb (9.5 kg). On a mass per unit time basis, the ash deposition rate on the CAH tubes would be 0.10 lb/hr (45.4 g/hr) of coal firing. Incorporating the surface area of the tube bank (6.28 ft^2 or 0.58 m^2) results in a value of 0.017 lb/hr-ft^2 (78.3 g/ hr-m^2). On a coal-firing-rate basis, the CAH ash deposition rate would be 0.04 lb/MMBtu (18.2 g/10^6 kJ). Although a comparison with a previous subbituminous coal-fired test is not possible, a comparison with recent Illinois No. 6 coal-fired tests indicates similar ash deposition rates based on the ash content and heating value of the fuel. On a lb/MMBtu (g/10^6 kJ) basis, the ash content of the Cordero Rojo coal was 62% of that observed for the Illinois No. 6 coal. Calculated ash deposition rates for the March test firing the Cordero Rojo coal were nominally 66% of those calculated for the Illinois No. 6 coal-fired test completed in December 1999. However, the relative value of this comparison is limited because the slag screen configuration was different (18 tubes in March versus 9 tubes in December) as was the approach to CAH sootblowing (8 hr frequency in March versus 24 hr in December). Comparisons with other SFS tests are not appropriate because sootblowing of the CAH tube bank was only routinely used during the December 1999 and March 2000 SFS tests. Routine sootblowing of the CAH tube bank was again used during the June SFS test. However, data and observations from the June SFS test are not available for inclusion in the report.

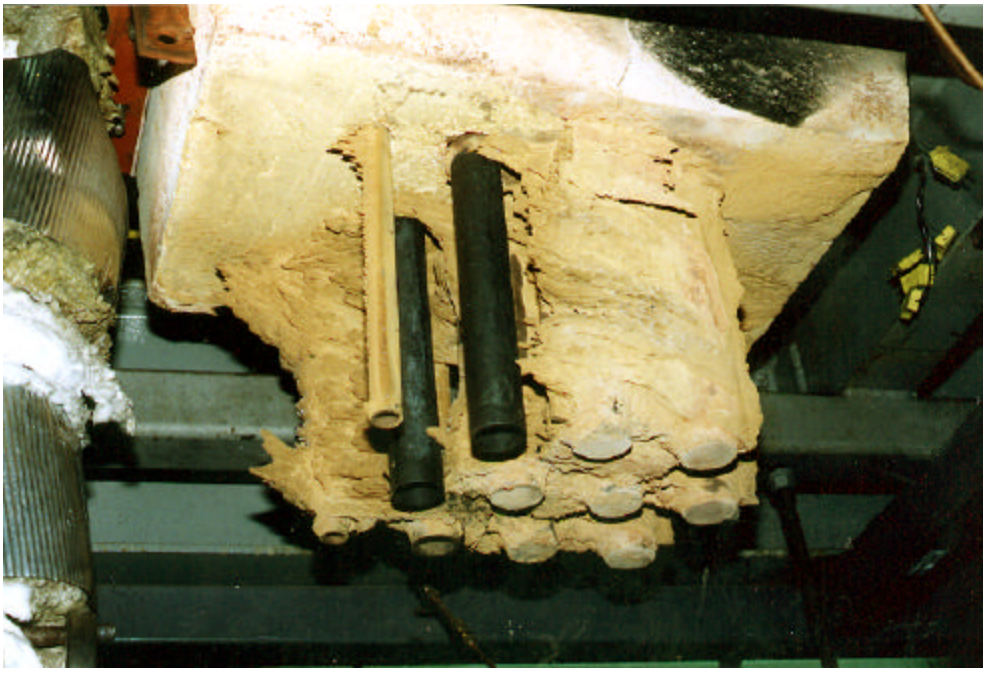

Exhibit 2-15 Photograph of Ash Deposits on the CAH tubes Following the March Test Firing

Testing of the RAH Panel

Initial shakedown and testing of the RAH panel took place in December 1997. Testing of the RAH panel continued this past quarter with completion of an SFS test in June 2000. However, data from the June test are not available for discussion at this time. Therefore, the balance of the RAH discussion will focus on data and observations resulting from an SFS test completed in March 2000. The primary purpose of the March (SFS-RH12-0200) test was to evaluate the ability of a Kyocera tile to withstand the slag attack and thermal cycling conditions in the slagging furnace. In addition, RAH panel performance was evaluated

relative to heat transfer, tile and tube temperatures, and process air temperatures and flow rates. Generally, the performance of the RAH panel in March was nominal, with no significant process or material problems observed.

A set of ceramic tiles (originally installed in January 1999) were removed from the RAH panel in November 1999 in preparation for the installation of new tiles in December. The RAH panel ceramic tiles were thoroughly inspected upon installation. Exhibit 2-16 illustrates the cracks found in the tiles/bricks, and Exhibit 2-17 is a photograph of the furnace interior after the new tiles were installed. The three new fusion-cast alumina Monofrax M tiles (small upper tile, large lower tile, and small lower tile) had minor cracks. In addition, the small lower tile had one significant crack that extended from the top to the bottom edge. None of these cracks is visible in the photograph.

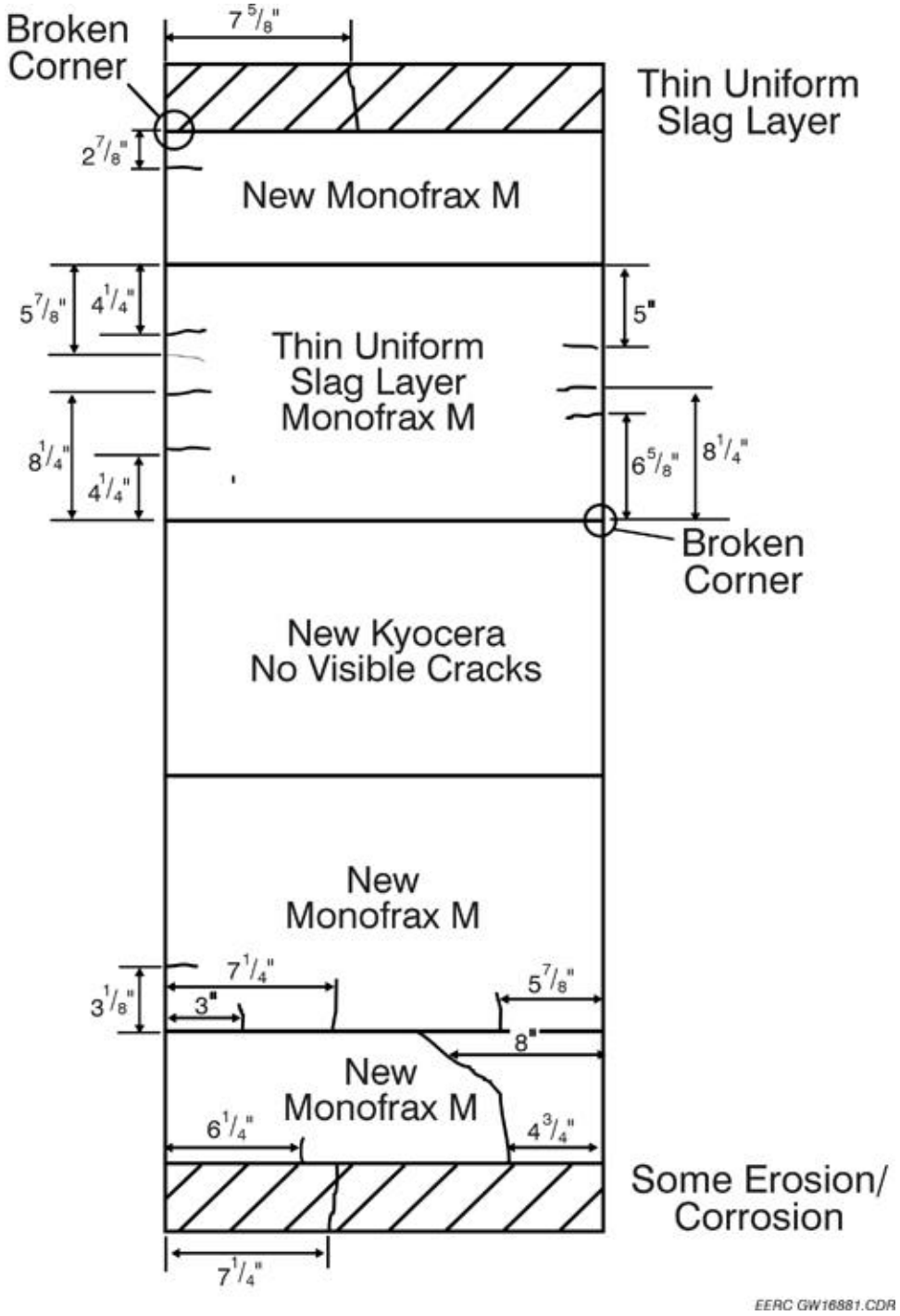

Exhibit 2-16 Illustration of Cracks Found in the Ceramic Tiles/Bricks Prior to the in the December 1999 Test, SFS-RH11-0799

Only one new sintered chromia–alumina Kyocera tile was installed because a second tile had four broken corners as well as a large number of small cracks extending from each edge. The damage to the second Kyocera tile occurred as a function of curing and machining prior to shipment to the EERC. The new Kyocera tile was installed in the center tile position and did not have any visible cracks. However, the upper right corner of the Kyocera tile was broken as a result of some machining that was performed at the EERC prior to its installation. Because only one large new Monofrax M tile was available, it was necessary to reuse one of the Monofrax M tiles originally installed in January 1999 as a replacement for the second

Kyocera tile. This large tile had been in the lower position on the panel and was placed in the upper position, as seen in the Exhibit 2-17 photograph. Five cracks were evident in this tile prior to the December 1999 test, four extending from the left edge and three extending from the right edge. The top and bottom support bricks were reused, with each having one vertical crack extending through the face.

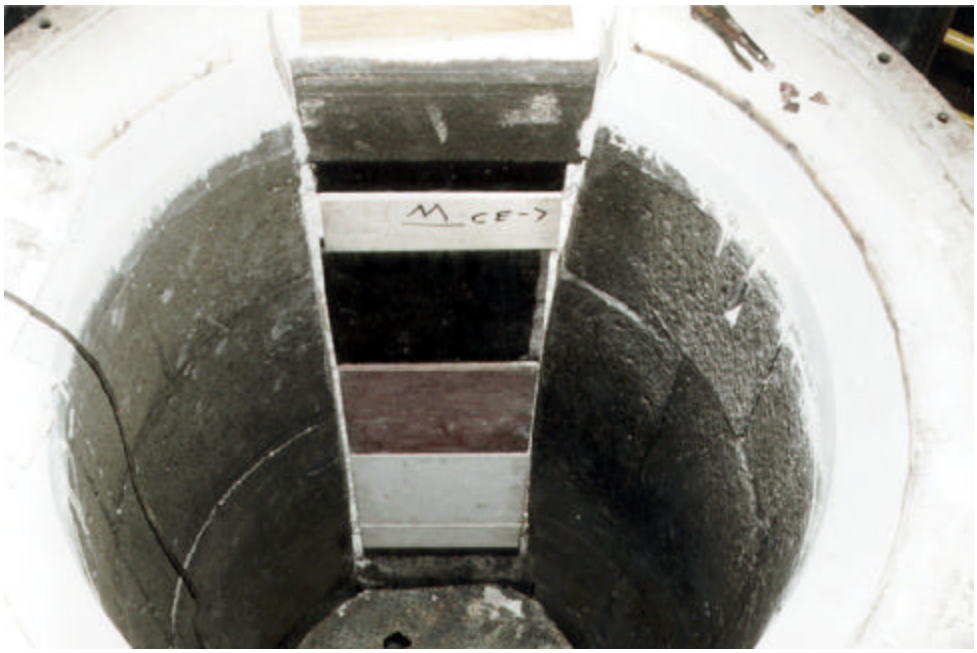

Exhibit 2-17 Photograph of the Ceramic Tiles Installed on the RAH Panel Prior to a December 1999 Test

The RAH panel ceramic tiles were thoroughly inspected following the March test period. Exhibit 2-6 presents a photograph of the RAH panel inside the furnace after the March test. Although the condition of the RAH ceramic tiles is not clearly depicted in this photograph, the Kyocera tile (large center tile) is somewhat evident from its color and surface characteristics. The Kyocera tile has a reddish hue in some areas where the slag coating is very thin or absent when compared to the Monofrax M tiles and the surface appears smoother. Although not obvious in the photograph, the degree of erosion/corrosion is more pronounced on the Monofrax M tiles.

The slag layer on the tiles is thin and appears to be uniform, with no evidence of any extensive slag buildup. While slag is present in the seams between the tiles, there is no evidence of any fusion between adjacent tiles. Therefore, the 2-hr period of natural gas firing at full load in March prior to SFS cooldown appears to have been adequate to prevent buildup of excess slag on the surface of the tiles or in the seams between tiles. Also, any quantity of slag present in the seams between tiles appears to crack as a result of cooldown and tile movement.

A residual slag layer on the surface of the new Monofrax M tiles following coal firing in December 1999 caused the surface of the tiles to darken, white to a brown/black. For the Kyocera tile, the color change was from a reddish hue to a gray. Exhibit 2-18 is a photograph of the small upper Monofrax M tile removed from the RAH panel following the March test. The tan or light colored areas on the surface of this tile are not consistent with previous observations and are the result of severe erosion/corrosion of the tile surface during the March test. The factors responsible for the degree of erosion/corrosion observed are believed to include the corrosive properties of the slag resulting from the Cordero Rojo fuel and the fact that this tile

is effectively insulated from the heat-transfer surfaces in the radiation cavity resulting in higher surface temperatures than the three large tiles. Plans for characterization of this tile are uncertain at this time.

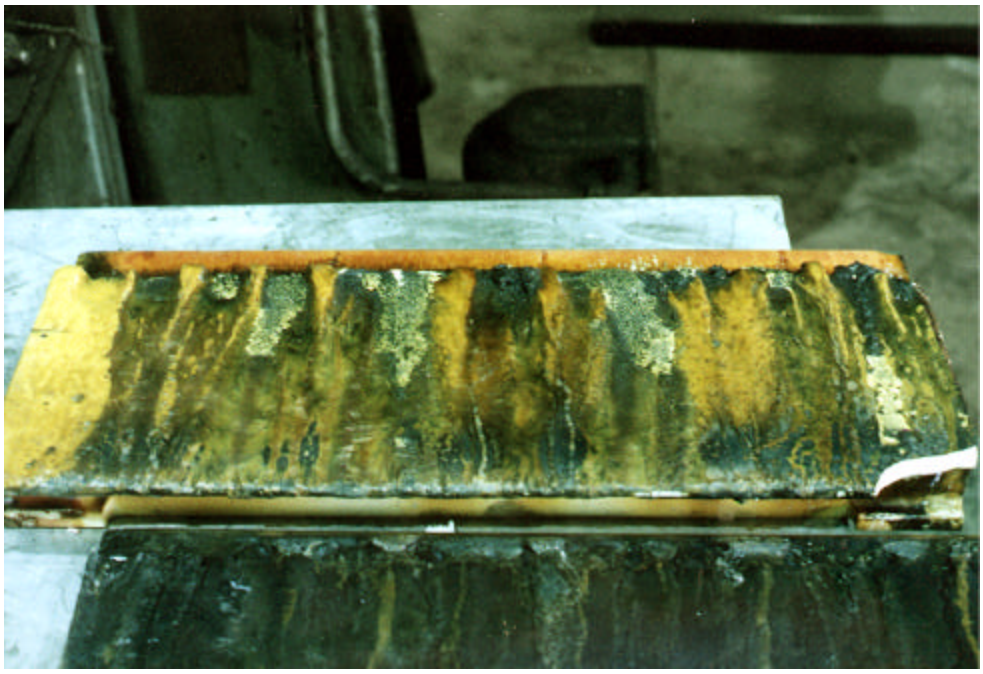

Exhibit 2-18 Photograph of the Small Upper Monofrax M Tile Removed from the RAH Panel Following the March 2000 Test

Exhibit 2-19 is a photograph of the large upper Monofrax M tile removed from the RAH panel following the March test. The appearance of this tile and the degree of erosion/corrosion are consistent with other Monofrax M tiles exposed to a variety of fuel/slag types. This tile has been exposed to furnace conditions for the greatest length of time and as a result shows the greatest degree of erosion/corrosion when the three large tiles are compared. The tile was originally installed in the RAH panel in January 1999 and was originally located in the bottom tile position.

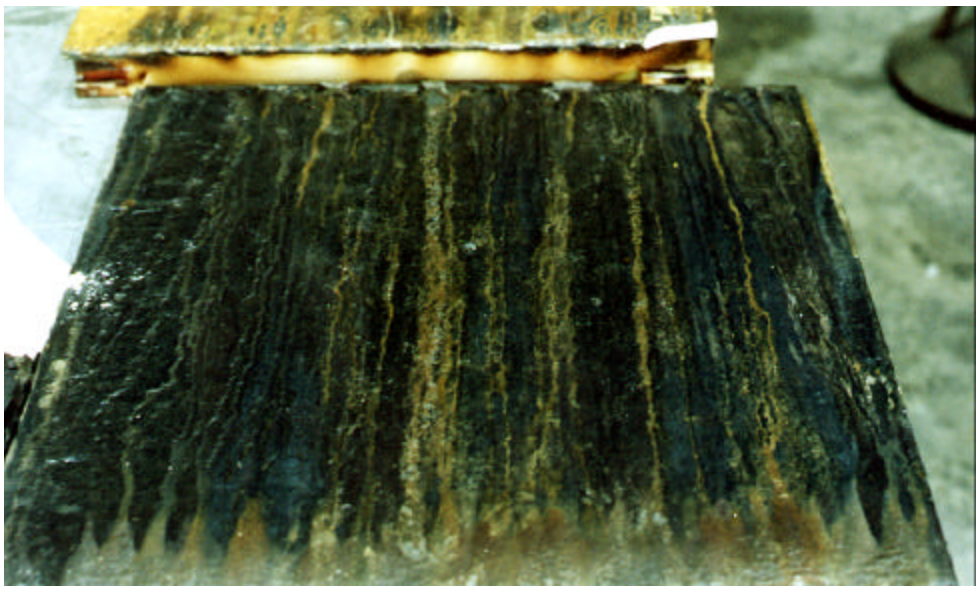

Exhibit 2-19 Photograph of the Large Upper Monofrax M Tile Removed from the RAH Panel Following the March 2000 Test

Exhibit 2-20 is a photograph of the large Kyocera tile removed from the center position of the RAH panel following the March test. The appearance of this tile and the degree of erosion/corrosion are consistent with expectations based on observations concerning the Monofrax M tiles. A coating of slag generally covers the surface of the tile. The most significant area of erosion/corrosion is observed at the top edge where slag dripped from the tile above. Slag channels that developed on the surface of the Kyocera tile are also evident in the photograph. Compared to the Monofrax M tiles, there were fewer corrosion channels, and they were not nearly as deep. In addition, the slag did not appear to penetrate into the Kyocera tile nearly as much as into the Monofrax M tiles. An interesting feature of the slag corrosion of the Kyocera tile is the formation of spots of frozen slag near the bottom of many of the slag corrosion rivulets. The spots of frozen slag are reddish in color and highly crystalline. It is believed that the spots formed as the slag dissolved enough of the chromium from the tile to increase the melting point of the slag to the degree that crystals formed and precipitated from the slag. Quantitative measurement of slag erosion/corrosion on the Kyocera tile should be possible as a result of tile sectioning and characterization.

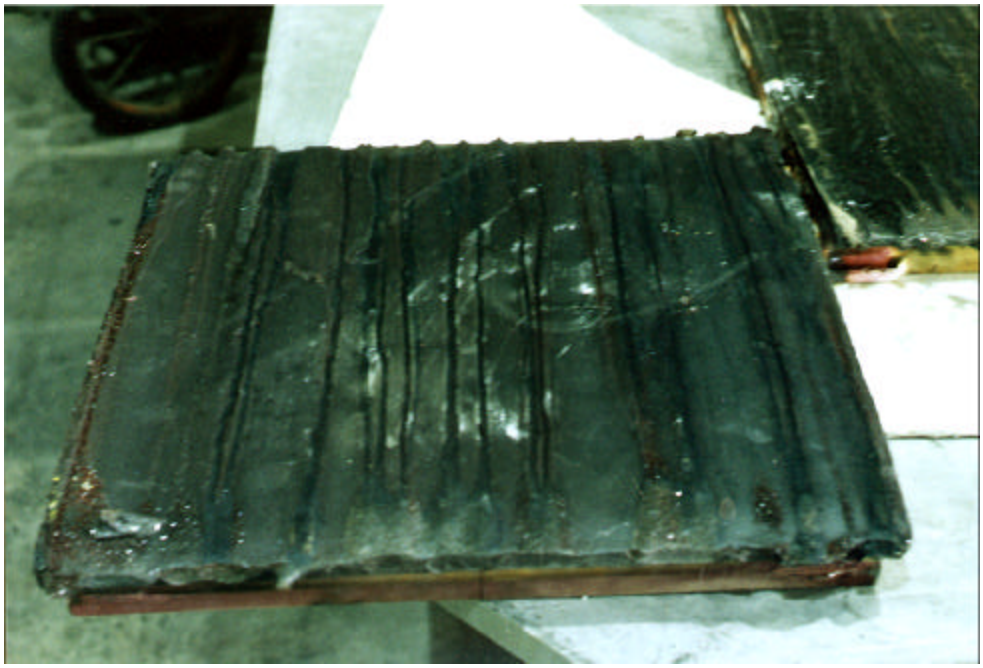

Exhibit 2-20 Photograph of the Large Kyocera Tile Removed from the RAH Panel Following the March 2000 Test

Exhibit 2-21 is a photograph of the large and small lower Monofrax M tiles removed from the RAH panel following the March test. These tiles were newly installed prior to the December 1999 test. The appearance of these tiles and the degree of erosion/corrosion are consistent with other Monofrax M tiles exposed to a variety of fuel/slag types. The small lower tile has generally shown the greatest degree of erosion/corrosion. This is believed to result from the combination of its higher surface temperature and the greater quantity of slag flowing over its surface during SFS tests relative to the other tiles. The surface temperature of the small tiles (both upper and lower), although not measured, is believed to be higher than the three larger tiles, because the backsides of these tiles are insulated and are not directly cooled by the heat-transfer surfaces. The greatest quantity of slag also flows over the lower tile because of its location below the other tiles. However, as previously stated, the small upper tile appeared to have suffered the greatest degree of erosion/corrosion following the March test.

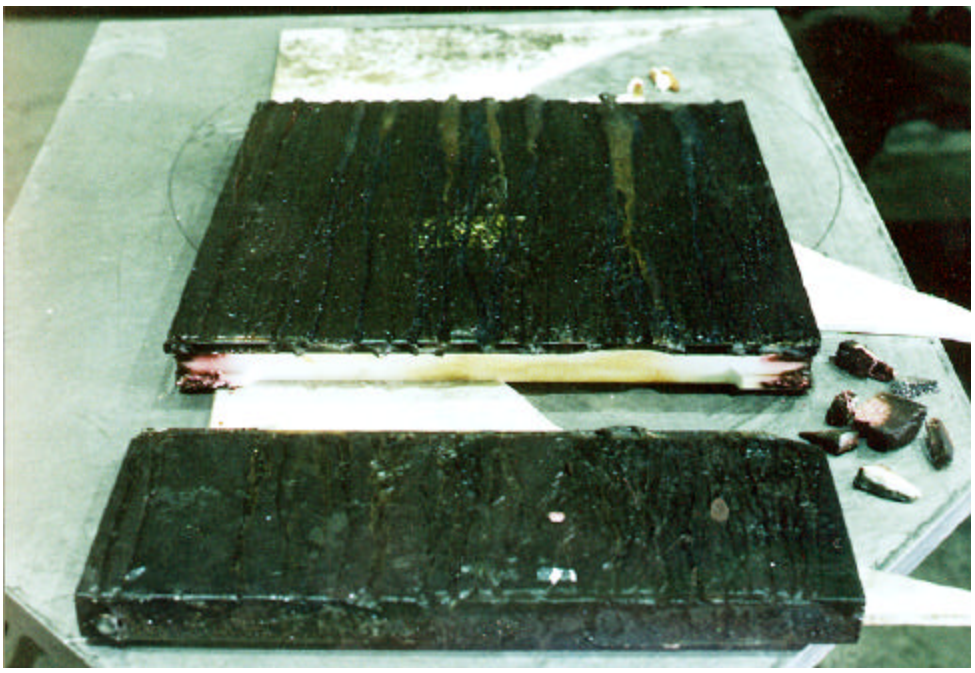

Exhibit 2-21 Photograph of the Lower Large and Small Monofrax M Tiles Removed from the RAH Panel Following the March 2000 Test

Exhibit 2-22 illustrates the visible cracks found in the RAH tiles following the March test. Overall, the condition of the tiles was degraded during the test. Following completion of the March test, only the small lower tile was observed to be free of visible cracks. However, at least one crack was evident in this tile prior to the December 1999 test, demonstrating the potential for hairline cracks to be covered with slag. A similar observation was made for the two large Monofrax M tiles. Seven cracks were evident in the large upper tile prior to the December test, with only three visible following the March test. Four cracks were evident in the large lower tile prior to the December test, with only two cracks visible following the March test.

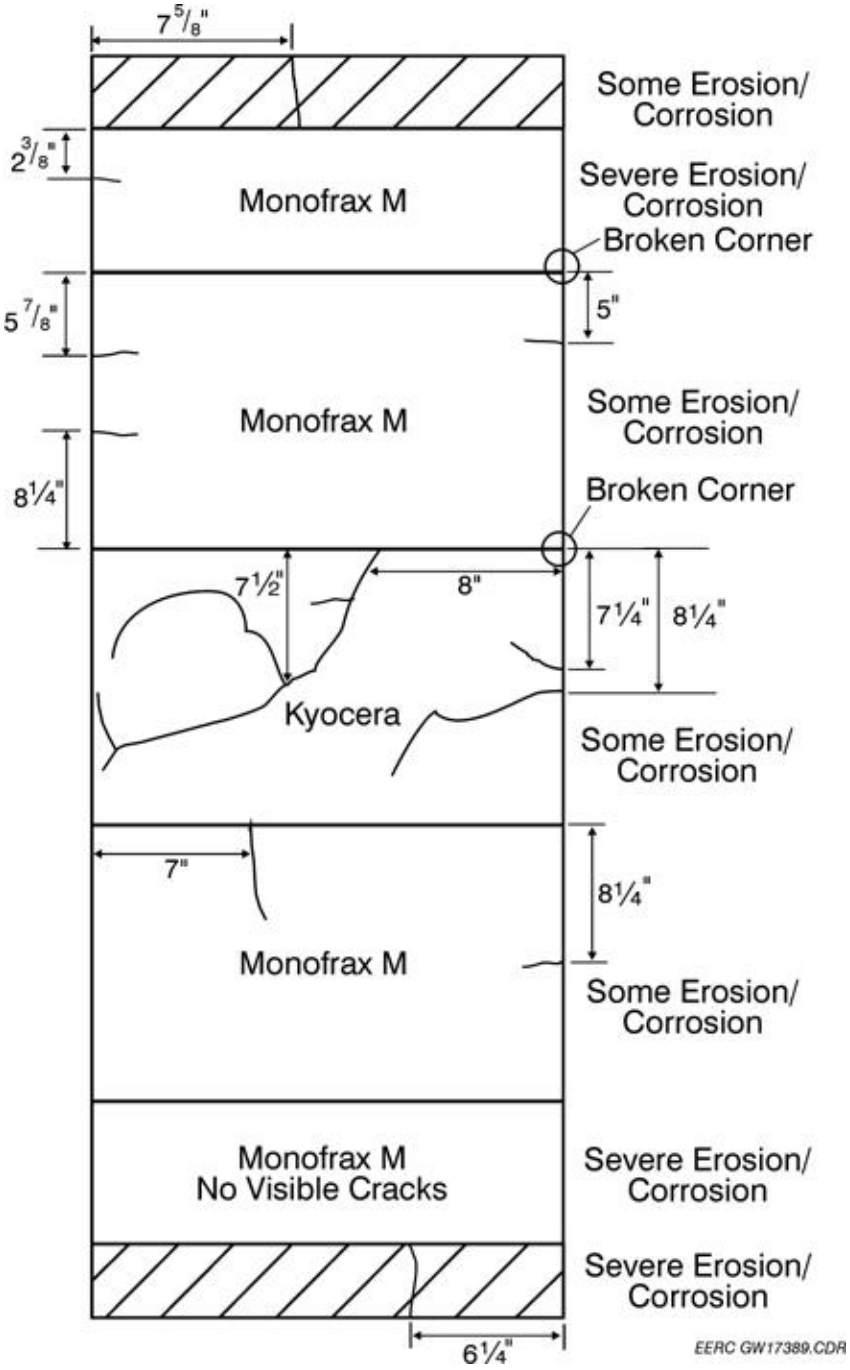

Exhibit 2-22 Illustration of Cracks Found in the Ceramic Tiles/Bricks of the RAH Panel Test

There were no visible cracks in the Kyocera tile prior to the December test. Following the December test, two cracks were evident originating from the right edge and one from the top edge. Following the March test, these three cracks were still visible, and two of the three had changed in appearance. The lower crack originating on the right edge had extended in length up and left, while a branch of the crack observed to extend down and left following the December 1999 test was apparently covered with slag and no longer visible. The crack originating from the top edge also changed in appearance as a result of the March test. The length of the crack extending up and left from near the center of the Kyocera tile had increased and turned down near the left edge. In addition, a lower branch of the crack increased its length to the left

creating a new visible branch in the crack. The lowest branch of the crack, originally observed following the December test, is no longer visible. This type of radial cracking was observed previously in one Monofrax M tile.

Heatup/cooldown cycles are believed to be the primary cause of RAH panel ceramic tile/brick crack propagation for both the Monofrax M and Kyocera tiles. Slag contributes to erosion/corrosion of surfaces and may impart stresses on the ceramic tiles as it finds its way into seams between tiles. The quantity of slag found in the seams between the tiles is small and always cracks during cooldown.

Exhibits 2-23 through 2-25 summarize the RAH ceramic tile temperatures, tube surface temperatures, and process air temperatures for the March test (SFS-RH12-0200). The process air flow rate data for the RAH panel were summarized in Exhibit 2-12. Exhibit 2-26 illustrates the location of thermocouples in the RAH panel, and Table 2-5 describes the RAH thermocouples.

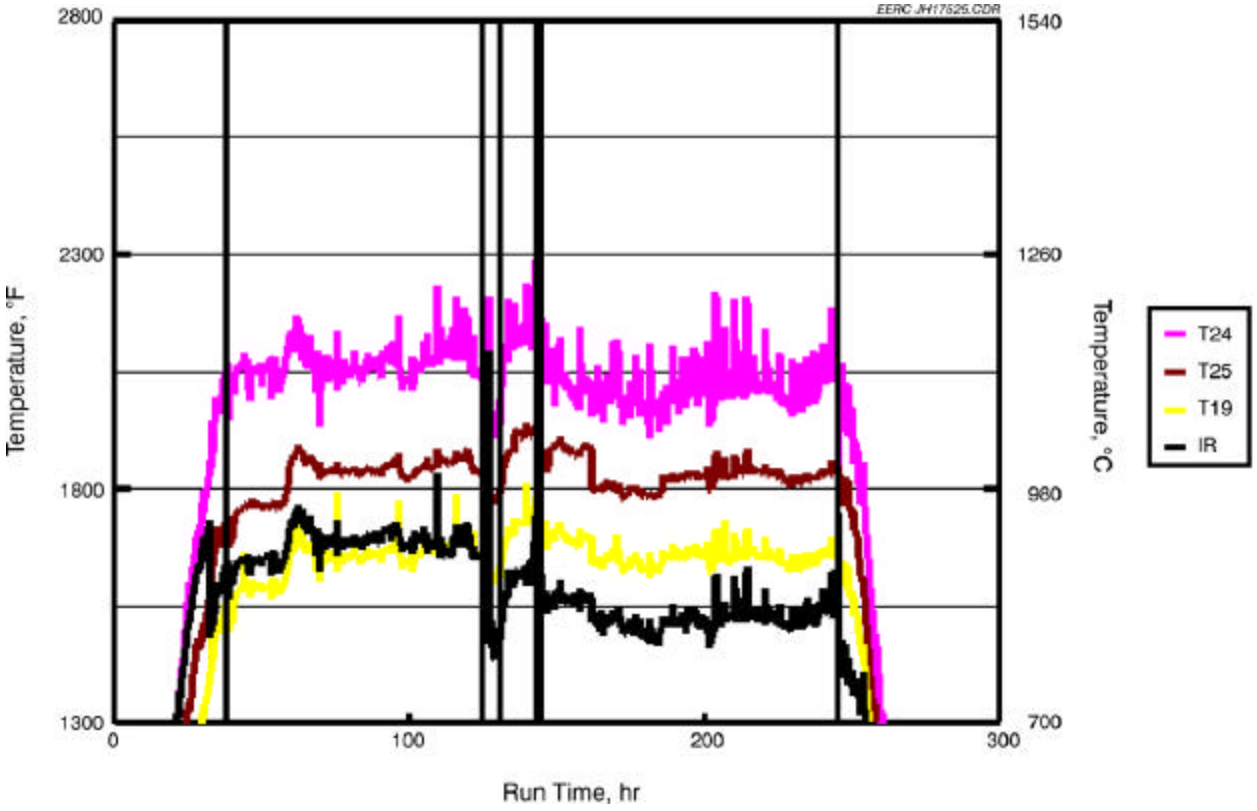

Exhibit 2-23 RAH Ceramic Tile Temperatures Versus Run Time for the March Test, SFS-RH12-0200

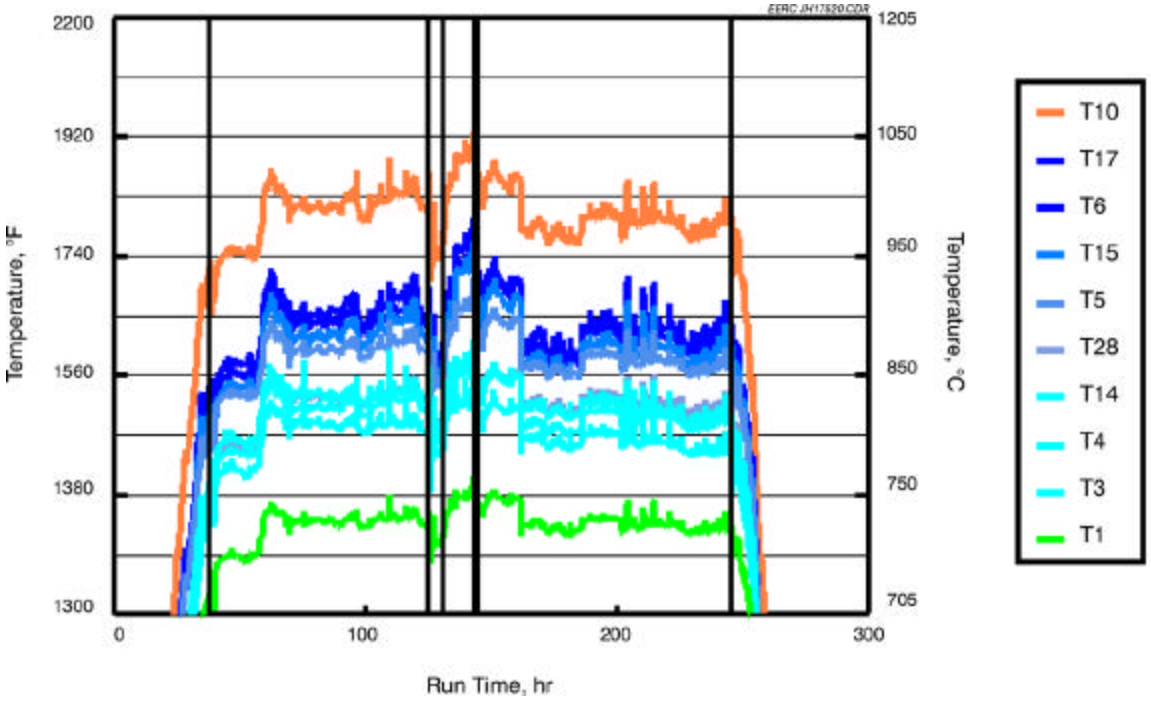

Exhibit 2-24 RAH Tube Surface Temperatures Versus Run Time for the March Test, SFS-RH12-0200

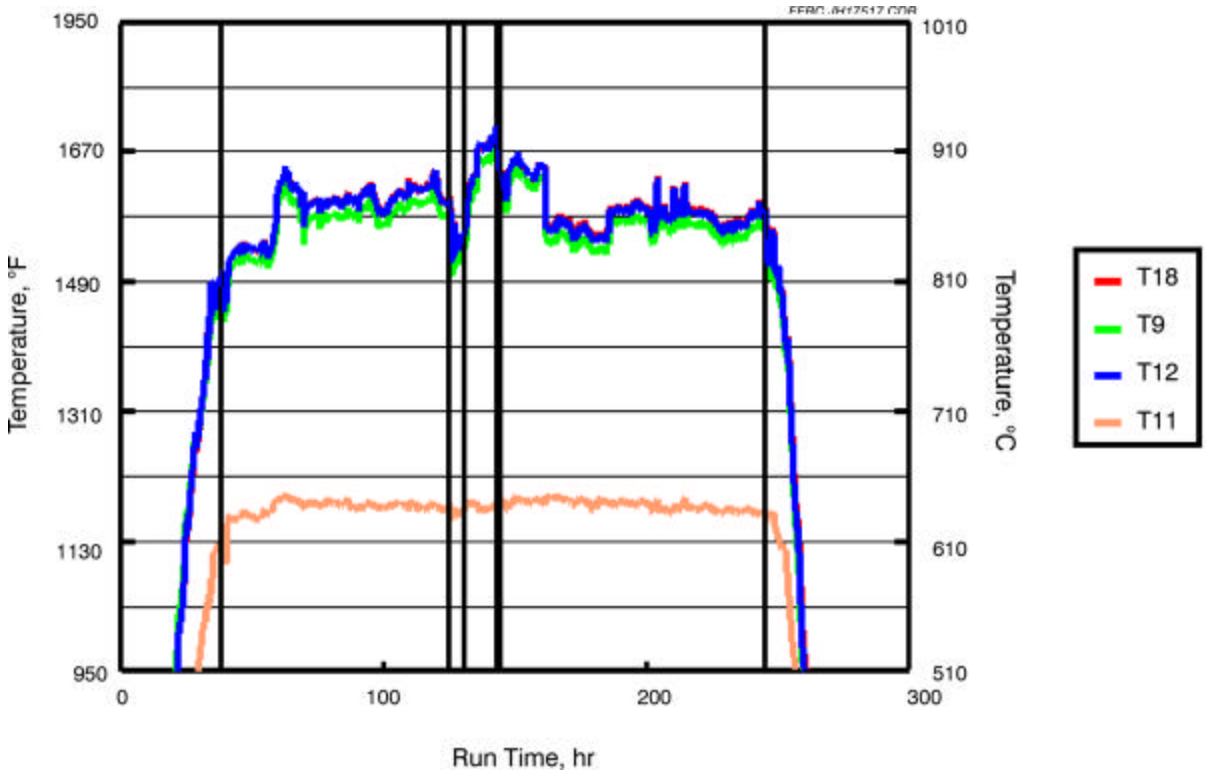

Exhibit 2-25 RAH Process Air Temperatures Versus Run Time for the March Test, SFS-RH12-0200 49

Table 2-5
Description of RAH Panel Thermocouple Locations[1]

Category	No.	Label	Description
Air Inlet	1	HP Air In	Provided by the EERC, in pipe before inlet header
	2	RAHT11	Air entering RAH through center tube
Air Outlet	3	RAHT18	Air leaving left (south) tube
	4	RAHT9	Air leaving middle tube
	5	RAHT12	Air leaving right (north) tube
MA Tube Surface	6	RAHT1	Top of middle tube facing cold side
	7	RAHT2	Middle of middle tube facing other tube
	8	RAHT3	Top of middle tube facing toward furnace
	9	RAHT4	Middle of middle tube facing cold side
	10	RAHT5	Middle of middle tube facing toward furnace (failed)
	11	RAHT6	Bottom of middle tube facing cold side
	12	RAHT7	Removed
	13	RAHT8	Removed
	14	RAHT10	Bottom of the middle tube facing toward furnace
	15	RAHT13	Removed
	16	RAHT14	Top of north tube facing toward furnace
	17	RAHT15	Bottom of north tube facing toward furnace (failed)
	18	RAHT16	Removed
	19	RAHT17	Bottom of north tube facing toward side wall
	20	RAHT28	Top of south tube facing toward furnace
	21	RAHT29	Bottom of south tube facing toward furnace (failed)
Inner Surface of Monofrax bricks	22	RAHT19	Top tile, center (failed)
	23	RAHT20	Removed
	24	RAHT21	Removed
	25	RAHT22	Middle tile, center (failed in December 1999)
	26	RAHT23	Middle tile (removed December 1999)
	27	RAHT24	Middle tile, left side rail
	28	RAHT27	Removed
	29	RAHT25	Lower tile, center (failed)
	30	RAHT26	Removed

[1] Thermocouple locations are illustrated in Exhibit 2-27.

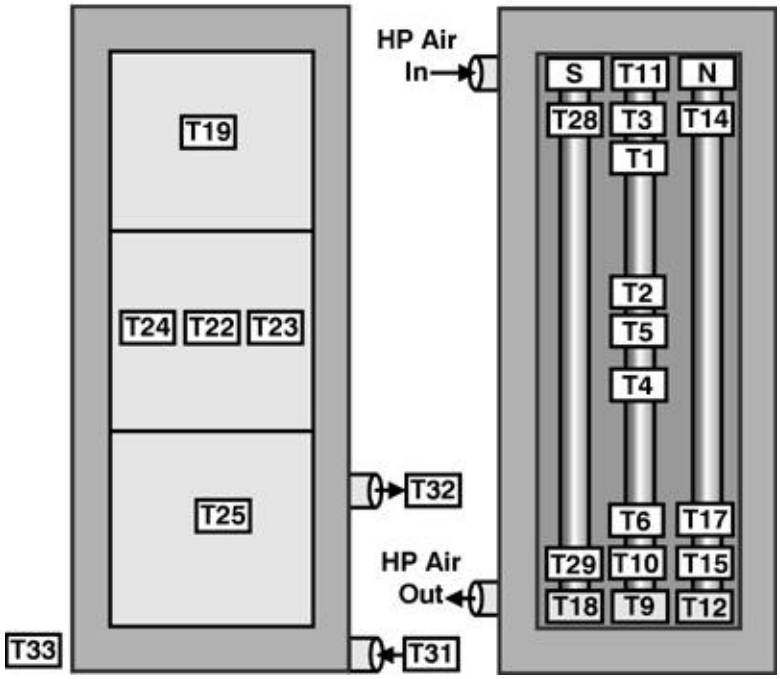

Exhibit 2-26 Thermocouple Locations in the RAH Panel

The indicated ceramic tile surface temperatures (cavity-side) ranged from nominally 1625° to 1890°F (885° to 1033°C), based on measurements made at the center of each of the three large tiles once the SFS had stabilized thermally (Run Hours 68 through 245). These measured temperatures are significantly lower than those observed during previous SFS tests. These thermocouple measurements were determined to be invalid as a result of an RAH panel inspection following the March test which found all three cavity-side thermocouples to be detached from the individual tile surfaces. Therefore, the thermocouples were simply measuring a cavity temperature. All three thermocouples were replaced and attached to the new RAH tiles installed prior to the June SFS test.

Thermocouple T23 was not used when the Kyocera tile was installed in December 1999. Therefore, a furnace-side tile surface temperature measurement was also not available in March. UTRC and the EERC elected to not install Thermocouple T23 to avoid potential damage to the Kyocera tile. This thermocouple was replaced and attached to the new RAH large center tile prior to the June SFS test.

RAH process air flow rates during the test were controlled at 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min), with most of the operational time split between 180 and 200 scfm (5.1 and 5.7 m^3/min). Changes in process air flow rates had a definite effect on tile surface temperatures, as indicated by cavity temperatures actually measured. As flow rates were reduced, tile surface temperature increased as indicated by increased cavity temperatures. Subsequently, when process air flow rates were increased, tile surface temperatures decreased. This effect is evident for flow rate changes at Run Hours 59, 147, 161, and 185.

RAH tube surface temperatures ranged from nominally 1425° to 1955°F (774° to 1069°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes. Tube surface temperatures in March were comparable to those for all previous coal-fired tests. However, three of the tube surface thermocouples had failed and

were not functioning for part if not all of the March test, including two of the three furnace-side thermocouples near the process air exit. These thermocouples were replaced prior to the June SFS test when the new tiles were installed.

Process air inlet temperatures ranged from 1195° to 1220°F (646° to 660°C) during the coal-fired operational period. Outlet process air temperatures ranged from nominally 1595° to 1725°F (869° to 941°C). The effect of process air flow rate can be seen in the process air outlet temperature data. As process air flow rate decreases, exit temperature increases, as expected. These flow rate changes are noted at Run Hours 59, 147, 161, and 185.

Heat recovery data from the RAH panel are presented in Exhibit 2-27 for the March test. At process air flow rates of 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min), the heat recovered from the RAH panel was 93,475 to 97,280 Btu/hr (98,616 to 102,630 kJ/hr), 100,000 to 102,550 Btu/hr (105,500 to 108,190 kJ/hr), and 100,900 to 107,500 Btu/hr (106,450 to 113,412 kJ/hr), respectively. The heat recovery ranges are a function of minor adjustments to the coal feed rate, combustion air flow rates, and changes in furnace pressure. The main burner firing rate was nominally 2.4 MMBtu/hr (2.5×10^6 kJ/hr).

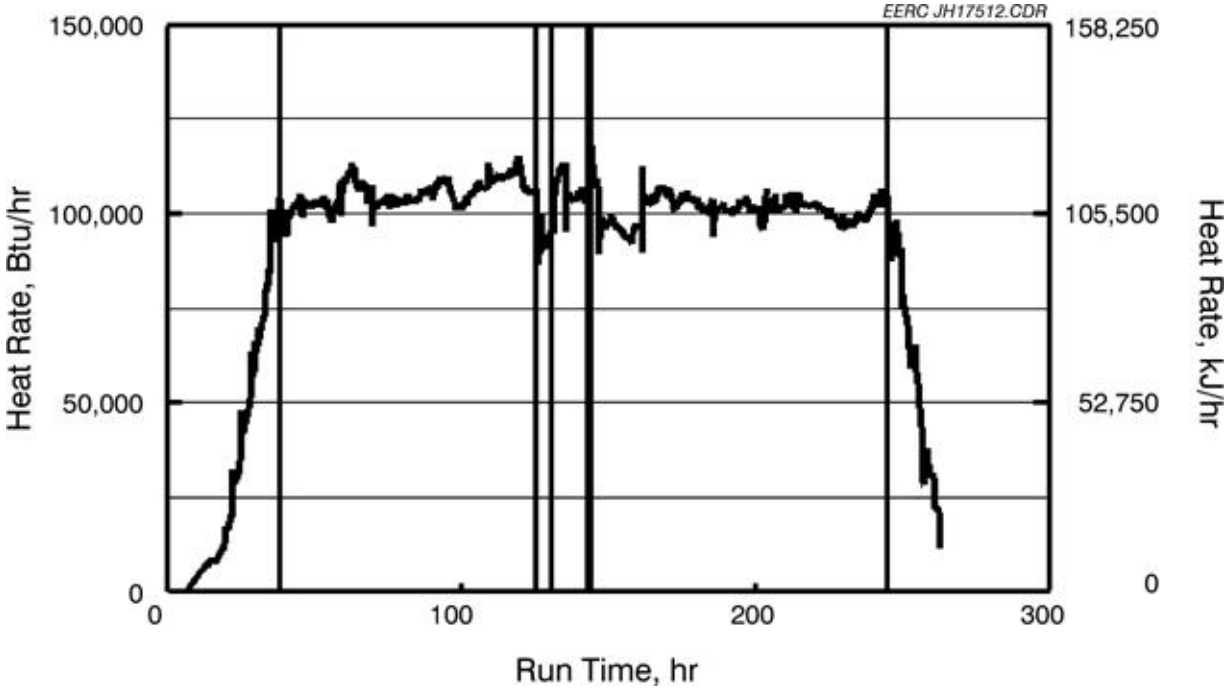

Exhibit 2-27 RAH Heat Recovery Versus Run Time for the March Test, SFS-RH12-0200

Exhibit 2-28 summarizes RAH heat recovery data at process air flow rates of 180 and 200 scfm (5.1 and 5.7 m^3/min) for bituminous coal-fired tests completed in 1998 through December 1999 and the subbituminous coal-fired test completed this past March. A comparison of Cordero Rojo coal-fired test data with previous high-moisture fuel tests (lignites and subbituminous coal) is not practical because of the presence of the small RAH panel during previous lignite fuel tests (April–June 1998) and a lower firing rate used during a previous subbituminous coal test (March 1998).

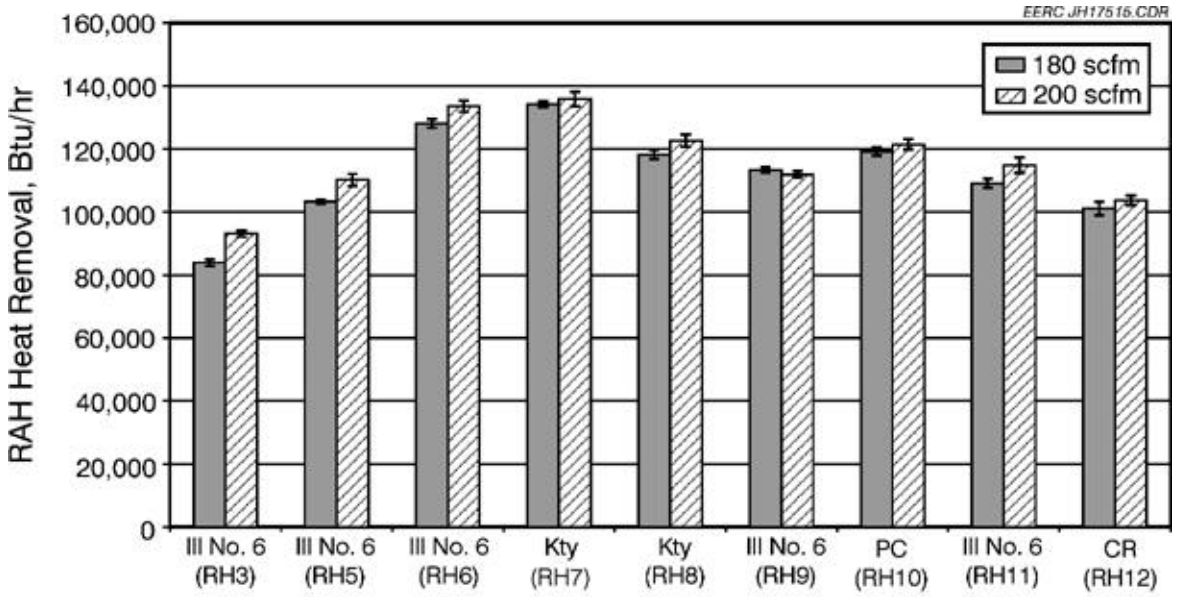

Exhibit 2-28 RAH Heat Recovery for Bituminous Coal-Fired Tests Completed in 1998, 1999, and the Subbituminous Coal-Fired Test Completed in March 2000

A comparison of the RAH panel data for the March (RH12) Cordero Rojo subbituminous coal-fired test and the Illinois No. 6 coal-fired tests previously completed indicates that the RAH heat recovery during the March test was better than RH3, similar to RH5, and lower than RH6, RH9, and RH11. Because of RAH tile replacement in late 1999 and furnace refractory conditions, the most reasonable data comparison is between RH12 and RH11. This comparison indicates that the heat recovery in March 2000 (RH12) was 8%–11% lower than that observed in December 1999 (RH11). On the basis of the data, this difference appears to be the result of furnace temperature differences. The furnace flue gas temperature along the wall near the RAH panel in March (RH12) was comparable to December (RH11), 2800° to 2850°F (1538° to 1566°C) versus 2795° to 2865°F (1535° to 1574°C). However, furnace flame temperature as measured by an optical pyrometer was 100°F (56°C) higher in December. This difference in flame temperature is the result of the higher fuel moisture content (25.3–26.1 wt% versus 2.8–3.2 wt%) of the Cordero Rojo coal. In addition, it was necessary to fire the main burner at a higher rate (nominally 20%) in March (nominally 2.4 MMBtu/hr [2.5 to 2.6 $\times$ 10^6 kJ/hr]) than December (2.0 to 2.1 MMBtu/hr [2.1 to 2.2 $\times$ 10^6 kJ/hr]) in order to achieve and maintain comparable furnace temperatures near the wall of the RAH panel. Again, the higher required firing rate for Cordero Rojo coal is the result of its higher fuel moisture content when compared to the Illinois No. 6 coal.

The reasons for the variations in RAH panel heat recovery rate are twofold. First, for tests up to and including the August 1998 tests, a small radiant air heater was also present in the furnace. This removed heat from the furnace and reduced the heat recovery rate by the RAH. After the August 1998 test, the small RAH was removed from the system. Therefore, direct comparisons of RAH heat recovery are only valid for tests completed over the past 18 months (RH6, RH7, RH8, RH9, RH10, RH11, and RH12). A second reason for heat recovery variability in the RAH can be seen in comparisons of RH6 and RH9 (firing Illinois No. 6 coal), and RH7 and RH8 (firing eastern Kentucky coal). In both cases, heat recovery by the RAH was lower for the second test for each coal type. These data indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation.

The reason for this reduction in heat recovery with time is not well understood, but there are several factors that could be influencing the reduction. One possibility is a potential change in heat flux to the RAH ceramic tiles resulting in a decrease in the heat transfer to the radiation cavity. The flame-side surface of the RAH ceramic tiles did darken as a result of slag coating and absorption during the January 1999 test. However, it is not clear what the effect would be on radiant heat absorption or emission, or thermal conductivity. Also, no additional color changes were noted following subsequent test periods. Another possibility is that the changing heat flow may be related to ceramic tile deterioration with each week of coal-fired furnace operation as a result of slag erosion/corrosion. Erosion/corrosion of the ceramic tiles may be affecting their heat-transfer properties. However, if thinning of the RAH ceramic tiles were the controlling factor, RAH heat recovery in December 1999 should have been higher than that observed in May 1999.

Another potential contributing factor to the decreasing heat flow may be the high-density furnace refractory color change observed with each week of operation. As the high-density refractory has darkened with each week of operation, it is possible that the reflectivity or emissivity characteristics of the furnace liner have changed, resulting in a decrease in radiation to the RAH panel. A combination of effects due to changes in tile and high-density refractory characteristics may be a reasonable explanation. That combination of factors would explain a lower RAH heat recovery rate in December 1999 (RH11, new tiles and aged high-density refractory) when compared to January 1999 (RH6, new tiles and high-density refractory) yet a comparable RAH heat recovery rate when compared to May 1999 (RH9, aged tiles and high-density refractory).

Table 2-6 summarizes operating time for the SFS, CAH tube bank, and RAH panel. Through May 2000, the RAH panel has been exposed to a range of furnace-firing conditions for a total of 2603 hr. Natural gas firing represents 1301 hr (including heatup, cooldown, and refractory curing), and coal/lignite firing represents 1302 hr. In addition, the RAH panel has been exposed to sixteen heating and cooling cycles. The RAH ceramic tile that was originally installed in January 1999 and reinstalled in December 1999 was exposed to nine heating and cooling cycles and 1598 hr of slagging furnace operation: 681 hr of natural gas firing (including heatup and cooldown) and 917 hr of coal firing. The new RAH ceramic tiles that were installed in December 1999 have been exposed to three heating and cooling cycle and 610 hr of slagging furnace operation: 208 hr of natural gas firing (including heatup, cooldown, and refractory curing) and 402 hr of coal firing. The longest continuous coal-fired period was 184 hr, completed in April 1999. This summary does not include SFS operation in late June 2000, a planned 200-hr test firing a Prater Creek bituminous coal. The SFS test completed in June is the last planned SFS test within EERC's subcontract. Data and observations resulting from the June test will be summarized in the July through September quarterly report.

Table 2-6
Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through May 2000

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	1904	1382	3286
CAH Tube Bank	1589	1349	2938
RAH Panel	1301	1302	2603

Other Project Activities

Other project activities completed this past quarter related to the pilot-scale effort included preparation of a paper for presentation at a conference and fabrication of a probe using MA 754 alloy for insertion in the slagging furnace during the June SFS test. A paper was prepared in April for presentation at the ASME IJPGC 2000 – International Joint Power Generation conference scheduled for July 2000. The paper describes the pilot-scale SFS and summarizes highlights relative to the performance of the CAH tube bank, RAH panel, and bench-scale slag management and materials work. The paper is titled "Testing of a Very High-Temperature Heat Exchanger in a Pilot-Scale Slagging Furnace System." The authors are Greg Weber and John Hurley of the EERC and Dan Seery of UTRC. The paper is included in Appendix A.

A small process air-cooled probe was fabricated in May using the MA 754 alloy. The probe was inserted into the slagging furnace during the June SFS test to evaluate the corrosion resistance of the alloy when it is exposed directly to the coal flame and slag as if the RAH were operated without the ceramic panels in place. The test was performed on the basis of the results of 1000-hr laboratory corrosion tests indicating that the slag will freeze on the surface of the alloy and that the corrosion rate will be extremely low. The laboratory data are reported in previous quarterly technical progress reports (October through December 1999 and January through March 2000). If the RAH can be operated without the ceramic panels in place, the design would be greatly simplified and the heat exchange coefficients would rise dramatically, requiring much less of the expensive alloy for RAH construction as well as elimination of the ceramic tiles.

The probe was inserted into the slagging furnace for a short period of time in May while the new high-density refractory was cured in the furnace, slag tap, and slag screen. However, the available process air required to control alloy temperature was insufficient, forcing the removal of the probe to avoid overheating the alloy. Changes were made to increase the quantity of process air available to support the probe prior to the June SFS test. As a result of the changes, it was possible to insert the MA 754 alloy probe into the slagging furnace once coal firing had been stabilized and leave it in place for nominally 130 hr of coal firing and the natural gas-fired cooldown period. Observations concerning the performance of the probe and the condition of the MA 754 alloy following the June test will be addressed in the July through September quarterly technical progress report.

TASK 2.2.5 – LABORATORY- AND BENCH-SCALE ACTIVITIES

In order to air-cool the MA 754 pipe to be exposed directly to the coal flame in the June test, it was friction-fit to the outside of an air-cooled 304 stainless steel bayonet heat-exchange probe. Thermal expansions of the two alloys were measured in May to determine if the friction fit would be maintained at temperature. The measurements indicate that the MA 754 will expand approximately 1.8% upon heating to 2000°F (1090°C). The 304 stainless has a greater expansion coefficient and will expand 1.8% upon heating to only 1800°F (980°C). Therefore, the friction fit will be maintained between the inner air-cooled 304 stainless and the outer MA 754 sleeve as long as the stainless is no more than 200°F (110°C) cooler than the alloy, which is expected to be the case. However, to help assure that the alloy sleeve will not slip off of the air-cooled probe, the ends of the two metals were cemented together with an alumina cement, and the probe will be maintained in a horizontal position.

Fifty pounds of slag from the March 2000 SFS test of the Cordero Rojo coal were ground in preparation for bench-scale refractory corrosion testing. Additionally, a paper describing the refractory corrosion work performed at the EERC under the Combustion 2000 project was presented at the Engineering Foundation Conference on Effects of Coal Quality on Power Plant Management in May. The paper is titled “Bench-Scale Measurements of Refractory Corrosion by Flowing Slag” and is included in Appendix B. The authors are John Hurley and Patty Kleven of the EERC and Will Sutton of UTRC.

Conclusions from the paper indicate that static corrosion tests are poor indicators of refractory performance when the slag fully penetrates into the refractory as it does for castable alumina-based materials. Instead, dynamic tests where the slag flows over the refractory are much more indicative of performance in a large-scale application. At temperatures near 1500°C, alumina-based cements provide acceptable service for testing purposes, whereas calcium aluminate cements do not. However, none of the refractories were acceptable for long-term commercial service. No refractory is universal in performance toward all slags. Alumina–cement refractories perform much better with acidic slags, but are easily penetrated by basic slags and burst through secondary crystallization. Alumina refractories with magnesium aluminate spinel additions perform better than pure alumina materials with more basic slags, but still do not provide adequate corrosion resistance. However, pilot-scale experience indicates that firing the refractory to higher temperatures, and especially coating it with more benign aluminosilicates, may substantially increase the lifetime of refractories exposed to basic slags at 1500°C. Rare-earth element additions to 99% alumina castables did not increase corrosion resistance or sintered strength. The most effective means of reducing alumina castable corrosion resistance may be addition of small amounts of alumina to the slag. An Illinois No. 6 slag to which only 3% alumina was added corroded an alumina castable by only one-third as much as the original slag at 1500°C.

APPENDIX A

TESTING OF A VERY HIGH-TEMPERATURE HEAT EXCHANGER IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

TESTING OF A VERY HIGH-TEMPERATURE HEAT EXCHANGER IN A PILOT-SCALE SLAGGING FURNACE SYSTEM

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KEYWORDS: Coal Combustion, Advanced Power System, High-Temperature Heat Exchanger

ABSTRACT

The University of North Dakota Energy & Environmental Research Center (EERC) is participating with United Technologies Research Center (UTRC) and UTRC subcontractors in Phase II of the Combustion 2000 high-performance power systems project, sponsored by the U.S. Department of Energy. EERC efforts have included laboratory- and bench-scale testing of materials used for the construction of key subsystems for a high-temperature advanced furnace (HITAF); testing methods to reduce problems related to coal slag flow and corrosion; and the design, construction, and operation of a pilot-scale slagging furnace system (SFS) to demonstrate essential HITAF subsystems.

This paper briefly describes the pilot-scale SFS and discusses pilot-scale results related to the performance of the convective air heater and radiant air heater. In addition, development of materials, additives, and strategies to reduce refractory and heat exchanger corrosion and modify slag behavior is discussed.

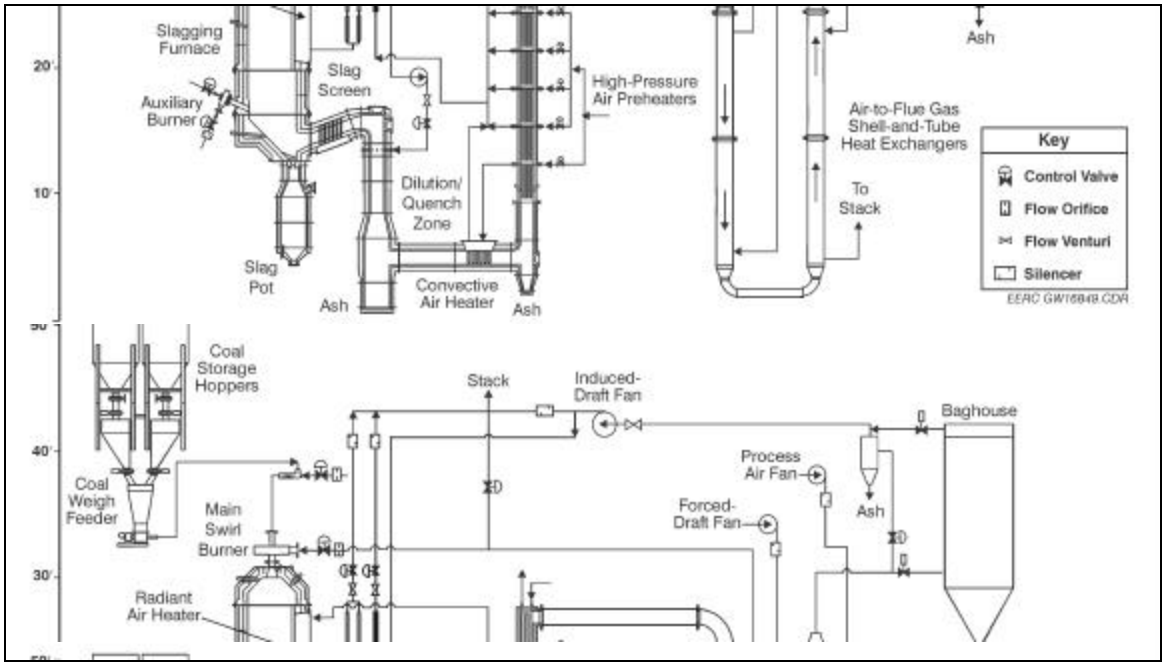
INTRODUCTION

In 1991, the U.S. Department of Energy (DOE) initiated the Combustion 2000 Program to help develop and commercialize a high-performance power system (HiPPS), with the goal of achieving 47% HHV (higher heating value) efficiency, only 1/10 of the particulate, and SO_x and NO_x emissions of modern plants, while reducing the cost of electricity by 10%. The United Technologies Research Center (UTRC) is leading one of the two teams developing HiPPS.

The heart of the UTRC system is a high-temperature advanced furnace, or HITAF, that uses heat exchangers and a duct burner to produce clean gas at 2600°F (1427°C) and 250 psig (17 bar) to turn an aeroderivative turbine, followed by a heat recovery steam generator and steam turbine. The overall design is very similar to that of a typical pulverized coal-fired boiler system, except that oxide dispersion-strengthened alloys are used to carry the very high-temperature air. This design makes it especially suitable as a potential boiler retrofit technology.

Calculations show that firing high-moisture fuels such as lignite in the HITAF incurs a 2% efficiency penalty when compared to the Illinois No. 6 coal but should still reach approximately 45% overall system efficiency. In addition, UTRC has calculated that with the use of a gas-fired duct heater, efficiencies can be increased from 47% to 55%, leading to reductions in CO_2 emissions of 40% compared to today's coal-fired systems.

Major EERC accomplishments in the project are the development of materials, additives, and strategies to reduce refractory and heat exchanger corrosion and the design, construction, and operation of the 3.0-MMBtu/hr (3.1×10^6-kJ/hr) slagging furnace system (SFS). Testing has shown that the furnace system reproduces full-scale heat-exchange and corrosion conditions very well and serves as an excellent test bed for key subsystems and materials. Pilot-scale SFS tests have indicated that the UTRC design for the high-temperature air heater is sound and that it can produce pressurized air at a temperature of up to 2000°F (1094°C).However, the use of ceramic panels to prevent slag corrosion of the alloy tubes requires further development.



DESCRIPTION OF PILOT-SCALE SFS

The pilot-scale SFS consists of eight main components: 1) slagging furnace, 2) slag screen/slag tap, 3) dilution-quench zone, 4) process air preheaters, 5) convective air heater (CAH) section, 6) radiant air heater addresses the performance of the pilot-scale slagging furnace, CAH tube bank, and RAH panel.

Pilot-Scale Slagging Furnace

The pilot-scale slagging furnace design is intended to be as fuel-flexible as possible, with maximum furnace exit temperatures of 2700° to 2900°F (1483° to 1593°C) to maintain the desired heat transfer to the RAH panel and slag flow. The furnace has a nominal firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr) and a range of 2.0 to 3.0 MMBtu/hr (2.1 to 3.2×10^6 kJ/hr) using a single burner. The furnace design was based on Illinois No. 6 bituminous coal (11,100 Btu/lb or 25,800 kJ/kg) and a nominal furnace residence time of 3.5 s. Flue gas flow rates range from roughly 425 to 645 scfm (12.0 to 18.6 m^3/min), with a nominal value of 530 scfm (15 m^3/min), based on 20% excess air. Firing a subbituminous coal or lignite increases the flue gas volume, decreasing residence time to roughly 2.6 s. However, the high volatility of low-rank fuels results in high combustion efficiency (>99%).

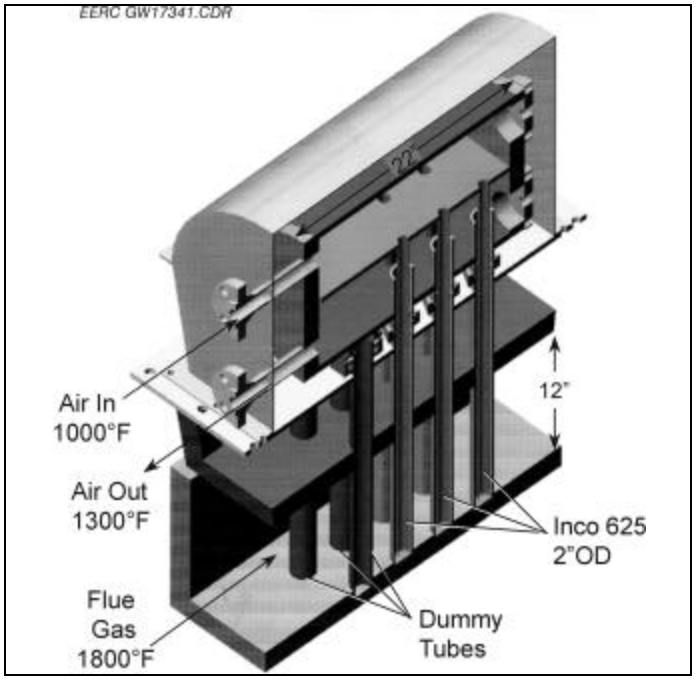
The Energy & Environmental Research Center (EERC) oriented the furnace vertically (downfired). Internal dimensions are 47 in. (119 cm) in diameter by roughly 16 ft (4.9 m) in total length. It is lined with three layers of refractory totaling 12 in. (30.5 cm) thick. The inner layer is composed of an alumina castable, developed by the EERC in cooperation with the Plibrico Company, that has been shown in bench and pilot tests to be resistant to slag corrosion.

Furnace flue gas temperature measurements are made using Type S thermocouples and three optical pyrometers (flame, near the RAH panel, and the furnace exit). Furnace temperature is also measured using thermocouples located at the interface between the high-density and intermediate refractory layers as well as between the intermediate and (RAH) panel, 7) tube-and-shell heat exchangers, and 8) pulse-jet baghouse. Figure 1 is a simplified illustration of the SFS. This paper insulating refractory layers. A pressure transmitter and gauges are used to monitor static pressures in order to monitor furnace performance. These data (temperatures and pressures) are automatically logged into the data acquisition system.

Convective Air Heater Tube Bank

The CAH design was a cooperative effort between the EERC and UTRC. The flue gas flow rate to the CAH tube bank has been calculated to range from 3553 to 4619 acfm at 1800°F (101 to 131 m^3/min at 982°C) depending on firing rate and fuel fired in the SFS. A rectangular inside duct dimension of 1.17 ft^2 (0.11 m^2) results in a flue gas approach velocity of 50 to 73 ft/s (15 to 22 m/s) to the CAH tube bank. Heat is recovered from the flue gas to meet process air temperature requirements to support the CAH. The design process air exit temperature from the CAH is 1200°F (649°C) at 150 psig (10 bar) and is not permitted to exceed 1300°F (705°C). Process air flow rate to the CAH tube bank typically ranges from 80 to 120 scfm (2.2 to 3.4 m^3/min) at nominally 1100°F (594°C) and controls process air exit temperature using a flow control valve. Process air exiting the CAH tube bank supports operation of the RAH panel.

Figure 2 is a simplified illustration of the CAH tube bank (Robson, et al., 1999). The CAH consists of twelve tubes installed in a staggered three-row array. The first five tubes in the flue gas path are uncooled surfaces designed to establish desired flue gas flow characteristics through the tube bank. In September 1998, the uncooled stainless steel tubes were replaced with three high-temperature alloy types (Incoloy MA956, Incoloy MA956HT, and PM2000). At the request of UTRC, two of these uncooled alloy tubes were removed from the CAH tube bank following a September 1999 test and returned to UTRC for characterization. The tubes removed from the CAH represent the alloys designated Incoloy MA956HT and Incoloy MA956. Replacement tubes were fabricated using 1.5-in. (3.8-cm) Schedule 40 stainless steel pipe.



The seven active (air-cooled) CAH tubes are 2-in. (5-cm) Inconel 625 tubing (0.188-in./0.478-cm wall). When originally installed, these tubes were not finned. However, in July 1998, fins were added in an attempt to improve heat transfer. The fins are 1-in. (2.5-cm) by 0.125-in. (0.318-cm) flat material and run the length of each tube on both the leading and trailing edges of the tube surface.

Radiant Air Heater Panel

A key design feature of the slagging furnace is accessibility for installation and testing of an RAH panel with respect to material lifetimes and heat transfer. The furnace will accept a panel with a maximum furnace-side dimension of 1.5 × 6.4 ft (0.46 × 1.96 m). This size was selected on the basis of panel-manufacturing constraints as well as a desire to minimize furnace heat losses. Flame impingement on the RAH panel is not necessarily a problem. Process air for the RAH panel is provided by an EERC air compressor system having a maximum delivery rate of 510 scfm (14.4 m^3/min) and a maximum stable delivery pressure of 275 psig (19 bar). A smaller backup compressor (300 scfm at <100 psig [8.5 m^3/min at <7 bar]) is available as well as a tie-in to a nitrogen system. UTRC designed and fabricated

the RAH test panel. Figure 3 is a simplified illustration of the UTRC RAH concept (Seery et al., 1997).

The RAH panel contains three vertically oriented tubes made of MA 754, a nickel-based oxide dispersion-strengthened alloy. The tubes are protected from slag corrosion by fusion-cast alumina refractory tiles. Process air, at 150 psig (10 bar), is heated from 1300° to 1700°F (705° to 927°C) as it passes through the RAH panel. Process air flow rate is used to control process air exit temperature using a flow control valve.

ACCOMPLISHMENTS

Table 1 summarizes hours of operation for the SFS, CAH tube bank, and RAH panel through March 2000 representing 23 thermal cycles. Natural gas firing includes heatup, cooldown, and refractory curing.

Seven different coal/lignite fuels have been fired in the SFS. Table 2 identifies these fuels, and Table 3 summarizes their characteristics. The North Dakota lignites represented the high end of the fuel moisture range, while the low end of the range was characteristic of the eastern Kentucky bituminous coals. Low ash content was characteristic of the eastern Kentucky bituminous coals and the subbituminous coals. The higher ash values were characteristic of the Illinois No. 6 coal. High sulfur was also characteristic of the Illinois No. 6 coal, with low sulfur (<0.5 wt%) representative of the subbituminous coals. The sulfur content of the eastern Kentucky bituminous coals and North Dakota lignites was also relatively low (<1 wt%). Heating values were highest for the eastern Kentucky coals (14,000 Btu/lb or 32,533 kJ/kg) and lowest for the lignites (<7200 Btu/lb or <16,731 kJ/kg). Ash fusion temperatures were lowest for the lignites as a result of the high alkali and low alumina content of the ash. The eastern Kentucky bituminous coals had the highest observed ash fusion temperatures because of the low alkali and iron content of the ash.

Slagging Furnace Performance

Coal feed rates to the slagging furnace have ranged from nominally 150 lb/hr (68 kg/hr) for the high-heating-value eastern Kentucky coals to 400 lb/hr (182 kg/hr) for a high-moisture lignite. Coal feed rate is typically controlled to maintain a furnace flue gas temperature of 2800°F (1538°C) in the vicinity of the RAH panel and furnace exit to the slag screen. Depending on fuel characteristics, the coal feed rate will result in a fuel firing rate of 2.1 to 2.7 MMBtu/hr (2.2 to 2.8×10^6 kJ/hr). In addition, an auxiliary natural gas-fired burner near the furnace exit is used to control furnace exit and slag screen temperatures by offsetting heat losses through the furnace shell and sight ports and to the RAH panel. Natural gas firing rates through the auxiliary burner are typically 0.35 to 0.7 MMBtu/hr (0.4 to 8×10^6 kJ/hr), representing 14% to 23% of the total furnace firing rate.

The coal firing rate in the slagging furnace has been increased on two occasions to achieve a furnace flue gas temperature of >2800°F (1538°C). The first occurred in August 1998, firing Illinois No. 6 coal, when the furnace temperature was increased to 2850°F (1566°C) in order to achieve a 2000°F (1094°C) process air temperature at the exit of the RAH panel. In September 1999, firing Prater Creek eastern Kentucky coal, the furnace temperature was increased to nominally 2900°F (1594°C) in order to facilitate slag flow from the slag screen through the slag tap. In general, the high-density alumina castable refractory, developed by the EERC in cooperation with the Plibrico Company, has been shown in the pilot-scale slagging furnace to be resistant to slag corrosion, more so for slags resulting from bituminous coal firing and less resistant to alkali slags resulting from subbituminous coal and lignite.

Replacement of the high-density refractory liner in the furnace has been necessary. However, although refractory corrosion was observed, refractory replacement was necessary to address problems related to shrinkage (top three furnace sections) and refractory cracking (main furnace section). As a result of initial curing, the high-density refractory experiences approximately 3% permanent shrinkage as predicted by Plibrico Company. However, some additional shrinkage or refractory densification is believed to occur with each subsequent thermal cycle. Refractory cracking in the main furnace section was primarily due to the

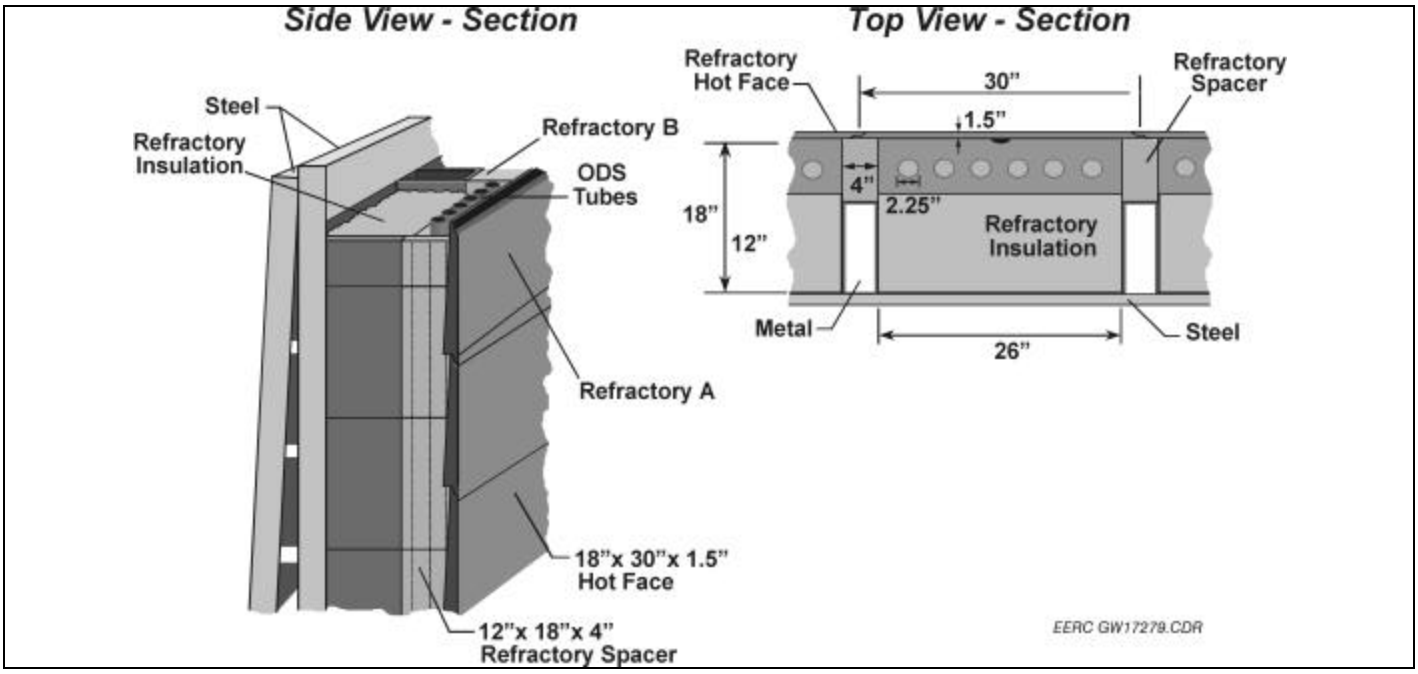


Table 1. Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through March 2000

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	1800	1382	3182
CAH Tube Bank	1485	1349	2834
RAH Panel	1301	1302	2603

Table 2. Fuels Fired in the SFS

Bituminous Coal	Subbituminous Coal	Lignite
Illinois No. 6	Rochelle	Coal Creek Station Lignite
Eastern Kentucky	Cordero–Rojo	Milton R. Young Station Lignite
Prater Creek		

Table 3. Fuel Characteristics

Moisture Content	2–38 wt%
Ash Content	4–12 wt%
Sulfur Content	0.3–4 wt%
Heating Value	6300–14,170 Btu/lb
Ash Fusion Temp., oxidizing	
Initial	2170°–2577°F
Softening	2180°–2600°F
Hemisphere	2190°–2620°F
Fluid	2200°–2680°F

original approach to high-density refractory installation. High-density refractory cracking has not recurred since the liner was replaced using an approach involving the pouring of 2-ft (0.6-m) castable lifts and the use of spacers creating 0.25-in (0.64-cm) gaps every 3 ft (0.9 m) around the circumference of the liner. This approach to high-density refractory installation appears to have satisfactorily addressed stresses related to thermal expansion and shrinkage with each furnace thermal cycle.

Convective Air Heater Performance

The CAH tube bank was installed and initially evaluated during a shakedown test completed in October 1997. Through March 2000, the CAH tube bank has experienced 2834 hours of operation, representing 18 thermal cycles. Natural gas firing (including heatup, cooldown, and refractory curing) represents 1485 hours, and coal/lignite firing represents 1349 hours. The CAH tube bank has met all performance goals relative to heat transfer and its support of the RAH panel. Performance differences relative to fuel ash properties were as expected. One issue not adequately addressed to date is effective sootblowing.

CAH tube bank performance has been evaluated as a function of CAH tube surface and flue gas temperatures, process air temperatures, and process air flow rate data. A single tube in the CAH was initially instrumented with five thermocouples to measure surface temperature. However, at this time, only one thermocouple continues to function properly. Twelve thermocouples measure process air temperature entering, within, and exiting the CAH tube bank. Based on thermocouple measurements, the clean tube surface temperatures are nominally 1550°F (844°C) when natural gas is fired. Heat recovery from clean CAH tubes is roughly 45,000 Btu/hr (47,475 kJ/hr) for a process air flow rate of 130 scfm (3.7 m^3/min), inlet process air temperature of 1035°F (558°C), outlet process air temperature of 1200°F (649°C), and flue gas temperature of 1800°F (982°C) entering the CAH tube bank. The addition of fins to the CAH tubes has had no effect on CAH heat recovery when the tubes are clean.

When Illinois No. 6 coal is fired, surface temperatures initially decrease at a rate of nominally 5? F/hr (2.8? C/hr) over nearly 25 hours as ash deposits develop on the surface of the tubes. Similar tube surface temperature degradation rates have been observed for other bituminous and subbituminous fuels. Degradation rates as high as 40? F/hr (22? C/hr) were observed for a lignite.

Heat recovery data for all bituminous, subbituminous, and lignite fuels fired in the SFS indicate that absolute heat transfer after 30 to 40 hours of coal/lignite firing was comparable (10,000 to 15,000 Btu/hr [10,550 to 15,825 kJ/hr]) for a given process air flow rate. Therefore, although more frequent sootblowing may be required for a given fuel, absolute heat recovery should be comparable independent of fuel type. CAH heat recovery data support the conclusion that the addition of the fins to the air-cooled tubes improves heat recovery during the coal-fired test periods. The fins appear to reduce the rate of heat-transfer degradation as ash deposits develop and help to maintain a higher heat-transfer rate once the deposits have formed.

Figure 4 is a photograph of the CAH tube bank following a200-hour Illinois No. 6 coal-fired test completed in December 1999. The photograph shows three of the five uncooled tubes as well as two of the seven air-cooled finned tubes. Substantial leading- and trailing-edge deposits are visible. However, no deposits were observed bridging the flue gas path between the tubes. This observation is consistent for all fuel types fired in the SFS.

Deposit strength is a function of ash chemistry, particle size, and temperature history. The relative strength of the deposits formed when Illinois No. 6 coal is fired is indicated by the fact that the deposits remained intact when the tube bank was removed from the duct. CAH ash deposits resulting from the eastern Kentucky bituminous coals and the subbituminous coals fired in the SFS were observed to have less strength. Deposit strength for the lignites fired was comparable to the Illinois No. 6 deposits in one case, with lower strength exhibited by a second lignite. However, similar deposits formed in full-scale boilers when this same lignite is burned can become very hard through in situ sulfation over longer periods of time.

Radiant Air Heater Performance

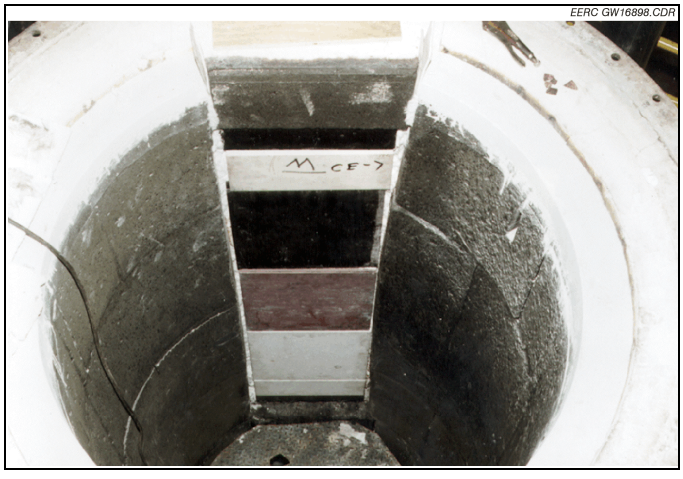
RAH panel performance is based on 2603 hours of operation, representing 16 thermal cycles. Natural gas firing (including heatup, cooldown, and refractory curing) represents 1301 hours, and coal/lignite firing represents 1302 hours. Initial shakedown and testing of the RAH panel took place in December 1997. The primary purpose of the SFS tests completed in the past 2 years was to evaluate the performance of the RAH panel relative to heat transfer, tile and tube temperatures, process air temperatures and flow rates, and the ability of the ceramic tiles to withstand slag attack and thermal cycling conditions in the slagging furnace.

Generally, the performance of the RAH panel has been consistent with UTRC expectations concerning heat transfer, with no significant process problems observed. Three different materials have been used to fabricate ceramic tiles to protect alloy heat-transfer surfaces from furnace conditions. These materials included a fusion-cast alumina Monofrax L, a fusion-cast alumina Monofrax M, and a sintered chromia–alumina Kyocera tile material. Although the Monofrax M material demonstrated better slag corrosion resistance than the Monofrax L material, neither material was found to have acceptable slag corrosion resistance for application in a commercial HITAF system. Limited pilot-scale testing to-date indicates that the sintered chromia–alumina Kyocera tile material is more resistant to slag corrosion than either of the Monofrax materials. Bench-scale flowing slag tests have shown recession rates for the sintered chromia–alumina Kyocera material to be 70% less than the Monofrax M materials and 91% less than the Monofrax L material (Weber et al., 1999; Hurley et al., 2000).

The RAH panel ceramic tiles were thoroughly inspected upon installation and following each SFS test. These inspections were important to document any tile cracking that may have occurred as a result of tile fabrication as well as exposure to slagging furnace conditions and thermal cycling. Most new fusion-cast alumina Monofrax L and M tiles have had visible hairline cracks prior to installation in the RAH panel. The hairline cracks found in new RAH tiles are believed to result from stresses encountered during tile fabrication, the actual casting/cooling process, and the machining of the tiles. These stresses and the resulting cracks could be reduced if the tiles could be formed in near net shapes, eliminating the need for machining. Also, thermal cycling is believed to be the primary cause of crack propagation for both the Monofrax M and Kyocera tiles. Slag contributes to erosion/corrosion of surfaces and may impart stresses on the ceramic tiles as it finds its way into seams between tiles.

Figure 5 is a photograph of the RAH panel prior to a December 1999 SFS test. The three white tiles (small upper and bottom tiles and large bottom tile) are new fusion-cast alumina Monofrax M tiles. The large, dark upper tile is a used Monofrax M tile, and the large center tile is a new sintered chromia–alumina Kyocera tile. In the photograph, the Kyocera tile appears grey in color, when actually it was a reddish hue before exposure to furnace conditions.

Figure 6 is a photograph of the RAH panel after the December 1999 test. Although the condition of the RAH ceramic tiles is not clearly depicted in this photograph, the Kyocera tile is evident from its color and surface characteristics. The Kyocera tile is lighter in color when compared to the Monofrax M tiles, and the surface appears smooth. Close examination of the tiles showed that the degree of erosion/corrosion was more pronounced on the Monofrax M tiles. Quantitative measurement of this difference will only be possible when the tiles have been removed from the RAH panel.



A residual slag layer on the surface of the new Monofrax M tiles following coal firing in December 1999 caused the surface of the tiles to darken from white to a brown/black. For the Kyocera tile, the color change was from a reddish hue to a gray. The color change in the Monofrax M tiles is consistent with previous observations for Monofrax tiles, and no additional color change is anticipated with further SFS operation. Further color changes to the Kyocera tile are not expected. Although not obvious in the photos, the slag layer on the tiles is thin and appears to be uniform, with no evidence of any extensive slag buildup. While slag is present in the seams between the tiles, there is no evidence of any fusion between adjacent tiles.

The most significant area of tile erosion/corrosion is observed at the top edge where slag drips from the tile above. Slag channels that developed on the surface of the tiles are evident in the photograph. Compared to the Monofrax M tiles, there were fewer corrosion channels on the Kyocera tile, and they were not nearly as deep. In addition, the slag did not appear to penetrate into the Kyocera tile nearly as much as into the Monofrax M tiles. An interesting feature of the slag corrosion of the Kyocera tile is the formation of spots of frozen slag near the bottoms of many of the slag corrosion rivulets. The spots of frozen slag are reddish in color and highly crystalline. It is believed that the spots formed as the slag dissolved enough of the chromium from the tile to increase the melting point of the slag to the point that crystals precipitated from the slag.

RAH ceramic tile, tube surfaces, and process air temperatures are continuously measured for each SFS test along with process air flow rate. Nominal ceramic tile surface temperatures (cavity-side) range from 2000° to 2170°F (1094° to 1188°C), based on measurements made at the center of each of the three large tiles. Furnace-side tile surface temperatures when measured were typically 2600° to 2700°F (1427° to 1483°C).

RAH alloy tube surface temperatures range from nominally 1360°to 2000°F (738° to 1094°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates have noticeable effects on all tube surface temperatures. Tube surface temperature step changes are most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes.

Process air inlet temperatures typically range from 1140° to 1250°F (616° to 677°C). Outlet process air temperatures range from nominally 1600° to 1800°F (871° to 982°C). On one occasion, process air exit temperature was permitted to reach 2000°F (1094°C) for a short period of time. This was accomplished at a process air flow rate and pressure of 100 scfm (2.8 m^3/min) and 100 psig (7 bar), respectively. Cavity-side tile surface temperatures at these conditions were nominally 2400°F (1316°C), with tube surface temperatures as high as 2200°F (1205°C).

RAH process air flow rates are typically controlled at 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min), with most of the operational time split between 180 and 200 scfm (5.1 and 5.7 m^3/min). Changes in process air flow rates are seen as step changes in tile and tube surface temperatures as well as RAH panel heat recovery.

Heat recovery data from the RAH panel for a December 1999 test were generated for process air flow rates of 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min). Heat recovered from the RAH panel was 101,430 to 106,700 Btu/hr (107,009 to 112,568 kJ/hr), 101,790 to 111,160 Btu/hr (107,388 to 117,274 kJ/hr), and 111,160 to 117,860 Btu/hr (117,274 to 124,342 kJ/hr), respectively. These heat recovery ranges are a function of minor adjustments to the coal feed rate and combustion air flow rates. The main burner firing rate was

nominally 2.0 MMBtu/hr (2.1×10^6 kJ/hr). These values compare favorably to the 98,000 Btu/hr (103,390 kJ/hr) rate predicted by the UTRC RAH heat transfer model for a 400°F (222°C) process air temperature rise.

Higher levels of heat recovery, 120,000 to 140,000 Btu/hr (126,600 to 147,700 kJ/hr), were observed during four previous test periods at process air flow rates of 180 and 200 scfm (5.1 and 5.7 m^3/min). These higher levels of heat recovery represent test periods firing bituminous coals and new or relatively new high-density furnace refractory. In general, the data generated since January 1999 indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation.

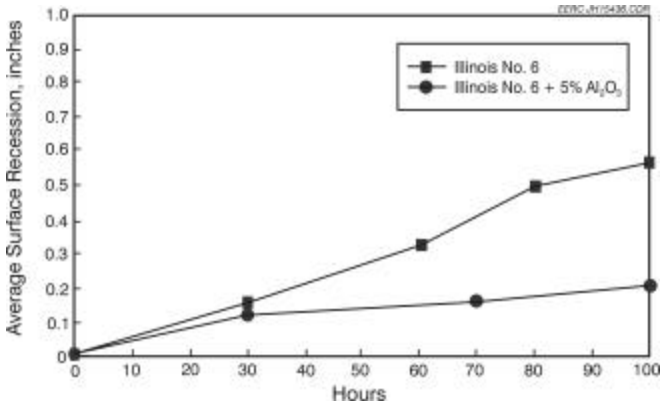
The reason for this reduction in heat recovery with time is not well understood, but EERC personnel believe that several factors are influencing the reduction. One possibility is a potential change in heat flux to the RAH ceramic tiles resulting in a decrease in the heat transfer to the radiation cavity. The flame-side surface of the RAH ceramic tiles do darken as a result of slag coating and absorption. However, it is not clear what the effect would be on radiant heat absorption or emission, or thermal conductivity. Also, no additional color changes are noted following the initial test period with new tiles.

Another potential contributing factor to the decreasing heat flow may be connected with the high-density furnace refractory color change observed with each week of operation. As the high-density refractory has darkened with each week of operation, it is possible that the reflectivity or emissivity characteristics of the furnace liner have changed, resulting in a decrease in radiation to the RAH panel. A combination of effects due to changes in tile and high-density refractory characteristics may be a reasonable explanation. That combination of factors would explain a lower RAH heat recovery rate observed with new tiles and aged high-density refractory when compared to new tiles and high-density refractory, yet a comparable RAH heat recovery rate when compared to aged tiles and high-density refractory.

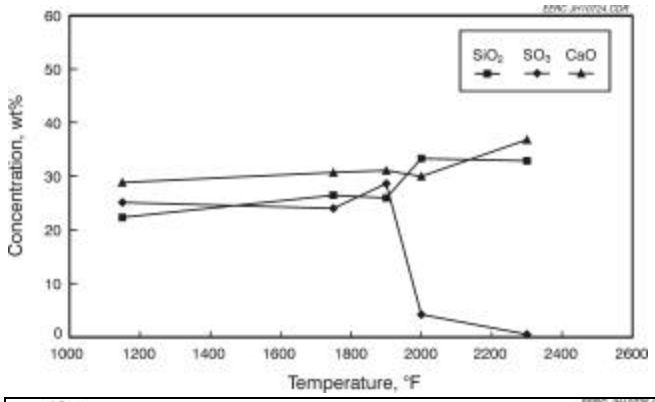
Two additional SFS test periods were planned prior to EERC completing its scope of work in support of UTRC's HiPPS project. One test period was completed in late March 2000, and the second is planned for June 2000. Future development efforts concerning the HITAF concept are uncertain at this time. Options being considered are focused on evaluating the performance of the RAH heat-transfer surfaces without the protective ceramic tiles in place.

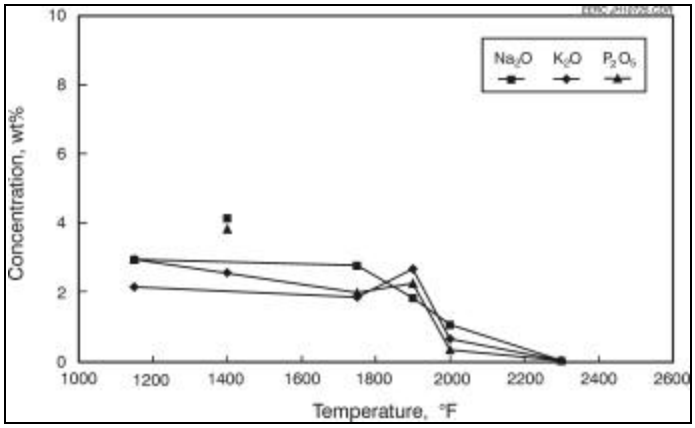
Methods to Reduce Corrosion

Corrosion of the refractory and ceramic tile surfaces by flowing slag is one of the greatest impediments to commercialization of the HITAF technology. The EERC is performing laboratory and bench-scale tests with a flowing slag reactor to develop methods of reducing the slag corrosion. Methods being investigated include selection of corrosion-resistant materials, use of corrosion-resistant coatings, slag additives, and careful selection of surface temperatures. One of the easiest methods to implement with specific types of coal is the use of additives to alter the corrosivity of the coal slag. Figure 7 illustrates the surface recession rate of a block of castable refractory, similar to that lining the SFS, when exposed to flowing Illinois No. 6 slag in the EERC bench-scale dynamic slag application furnace (DSAF) (Hurley et al., 2000). The refractory was fired to 2732°F (1500°C), then corroded at that temperature for 100 hours with flowing Illinois No. 6 slag with and without the addition of 5 wt% alumina. The additive causes the viscosity of the slag to increase, slowing the mass transport of the corrodents to the refractory surface, and may also partially saturate the slag with alumina, the primary constituent of the refractory. The data show that the alumina addition to the slag reduced the recession after 100 hours by over 60%. Addition of greater amounts of alumina to the slag should decrease corrosion rates even further. Also, the cost of adding the alumina to the coal is relatively low. For example, much less additive is needed to increase the alumina concentration in the slag by 10% than is needed to absorb sulfur species in a pressurized fluidized-bed combustor when firing a high-sulfur coal.



In addition to developing better materials or additives to protect the RAH heat exchanger tubes from corrosion, it may be possible to take advantage of the natural behavior of coal ash in order to operate the RAH without the need for the protective ceramic panels. In previous EERC work, a temperature window was identified in the thermochemical behavior of the products of coal combustion in which it is believed the products may be much less corrosive toward structural materials. The window ranges from a low of approximately 2000? F (1090°C) to an upper, fuel-dependent temperature of approximately 2300? F (1260°C). The lower end of the window is illustrated in Fig. 8, which shows the compositions of ash deposits collected from a utility boiler as compared to the nearby gas temperature (Hurley and Benson, 1995). Above the lower limit of the window, condensed sulfates and alkalies are not stable in the ash, so the corrosion of the alloys by these condensed materials should be significantly reduced. Below the upper limit, low-alkali coal ashes have very high viscosities so that the mass transfer of corrodents to the structural materials is relatively slow and a corrosion-reducing passive layer can exist. If such a low corrosion temperature window does exist, then it may be possible to operate the RAH without the protective ceramic tiles between the heat exchanger tubes and the flame. Removal of the tiles would significantly improve heat-transfer rates and simplify the design of the RAH so that time to commercialization of the RAH technology would be significantly reduced. The EERC is currently testing alloys to determine the extent to which operation in the temperature window may reduce corrosion rates.





CONCLUSIONS

The addition of fins to the air-cooled tube surfaces improved CAH heat recovery during coal-fired test periods. The fins appear to reduce the rate of heat-transfer degradation as ash deposits develop and help to maintain a higher heat-transfer rate once deposits have formed. However, no improvement in heat recovery was observed during natural gas-fired periods with clean tube surfaces. Also, the performance of an effective sootblowing system has not been evaluated.

Further development of ceramic tile material options is required to achieve performance objectives for the RAH panel. Optimization of materials and design are necessary with respect to slag erosion/corrosion as well as simplification of manufacturing to achieve technical and economic objectives.

Advances in heat exchanger materials and designs demonstrate that coal-/lignite-fired advanced power options can be developed and it may not be necessary to switch to natural gas firing or purchase CO_2 credits if CO_2 emission restrictions are legislated. Instead, existing coal-/lignite-fired boilers can be repowered with an indirectly

fired turbine combined cycle to increase efficiency by up to 50% and reduce CO_2 emissions by as much as 40%.

The HITAF concept offers a higher-efficiency technology option for coal-/lignite-fired power generation systems than conventional pulverized coal/lignite firing. Higher-efficiency technology options are important to the power generation industry in order to conserve valuable fossil fuel resources, reduce the quantity of pollutants (air and water) and solid wastes generated per MW, mitigate potential CO_2 emission limits, and reduce the cost of power production in a deregulated industry.

Design similarities of the UTRC concept to that of conventional pc-fired furnaces make it an ideal retrofit technology candidate. However, DOE has reduced funding for further development of the HITAF concept, so demonstration and commercialization of the technology are currently on hold.

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APPENDIX B

BENCH-SCALE MEASUREMENTS OF REFRACTORY CORROSION BY FLOWING SLAG

BENCH-SCALE MEASUREMENTS OF REFRACTORY CORROSION BY FLOWING SLAG

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Abstract

A bench-scale system has been constructed at the University of North Dakota Energy & Environmental Research Center (EERC) to reproduce flowing slag conditions that occur in coal-fired power systems. Named the dynamic slag application furnace, or DSAF, it can be used under controlled conditions to measure the rates and mechanisms of flowing slag corrosion of refractory materials at up to 1600? C. The test is useful for directly predicting the lifetime performance of the materials in air-blown environments. Comparisons between static and flowing slag test results for alumina-based monolithic materials show that static tests give very poor indications of probable performance in an operating system because the initial slag charge soaks into the refractory. In addition, static tests do not include erosion, which can greatly increase the loss rate.

Using the DSAF, EERC researchers have been working with the Plibrico Company and ALCOA to develop new types of castable refractories that are much more resistant to flowing slag corrosion than commercially available materials. Tests with both high-rank and low-rank coal slags show that it is not possible to choose one refractory composition that is universally resistant to all coal slags. However, if refractory composition is correctly matched to the slag composition, its lifetime can be significantly extended. In addition, small amounts of coal additives can dramatically reduce the corrosivity of the slag both by increasing the viscosity of the slag and reducing the ability of the slag to dissolve the refractory.

Introduction

In order to increase the efficiency of advanced coal-fired power systems, higher materials temperatures are necessary so that higher working fluid temperatures can be reached. Some system surfaces will have to be protected by covering them with refractories that are resistant to flowing slag corrosion. One proposed system is the United Technologies Research Center (UTRC) high-temperature advanced furnace (HiTAF), which is being developed under the U.S. Department of Energy Combustion 2000 program. The EERC is a major subcontractor to UTRC for that program. EERC activities include pilot-scale testing of major HiTAF subsystems, along with bench and laboratory-scale testing of the alloys, structural ceramics, and refractories. The refractory corrosion work is described in this paper.

Corrosion is the degradation of material surfaces or grain boundaries by chemical reactions with melts, liquids, or gases, causing loss of material and consequently a decrease in strength of the structure. In order to develop methods of reducing corrosion, the microstructure that is attacked must be identified along with the mechanism and rates of attack. Once these are identified, methods for reducing corrosion rates can be developed.

In order to determine the stability of a refractory in most industrial applications, various slag tests have been developed. The most common are the cup slag test, drip slag test (American Society for Testing and Materials [ASTM] C 768), gradient slag test, rotary slag test (ASTM C 874), and the dip-and-spin test. Among these tests, the cup slag test is the only static test method and the most commonly used. For flowing slag conditions, the drip or rotary test is most often used. However, in the rotary test, the slag charge is not renewed, so the slag can become saturated with corrosion products. Therefore, under the Combustion 2000 program, the EERC developed a variation of the drip test that uses a continuous flow of slag to better simulate the conditions in a slagging combustion system.

The initial focus of the work was to test the slag corrosion resistance of commercially available refractories and determine the mechanisms of their corrosion. The focus then shifted to improving the corrosion resistance of the near surface of the grains and bond phase between grains, since bonding phases normally have a lower melting point and lower corrosion resistance than does the bulk of the material. Other tests focused on the use of slag additives to decrease the corrosivity of the slag itself.

Experimental Methods

Two methods of testing the corrosion resistance of the refractories were used. The easiest to perform is the static test. In the static test, cubes 2 in. on a side with a 1-in.^{3} hole, or slag cup, in one surface were cast in a mold. After curing, the refractory cube was removed from the mold and fired at up to 2912? F (1600? C). Eleven grams of slag were placed into the slag cup and fired at 2732? F (1500? C) for 100 hours in air. The blocks were then cross-sectioned vertically through the slag cup, and the depth of slag penetration and surface recession was measured. The depth of slag penetration into the blocks is defined as the maximum depth at which measurable concentrations of the primary slag constituents of Si, Ca, and Fe are found in the blocks, as determined by elemental mapping using a scanning electron microscope (SEM).

For the dynamic slag corrosion tests, the DSAF is used. The DSAF was designed and built to simulate conditions of dynamic corrosion on the vertical wall of a refractory-lined slagging combustor. It is illustrated in Figures 1 and 2. The DSAF is a 23- by 23-in. double-chamber furnace, with each chamber gliding on

rollers away from the other in the open mode. It has the capability of testing refractory samples up to a maximum of 3092? F (1700? C) and is designed to handle up to four test samples simultaneously. It uses 14 molybdenum disilicide ($MoSi_2$) heating elements, with a 4-in.-thick insulation wall on the vertical walls and 5-in.-thick insulation wall on the horizontal walls.

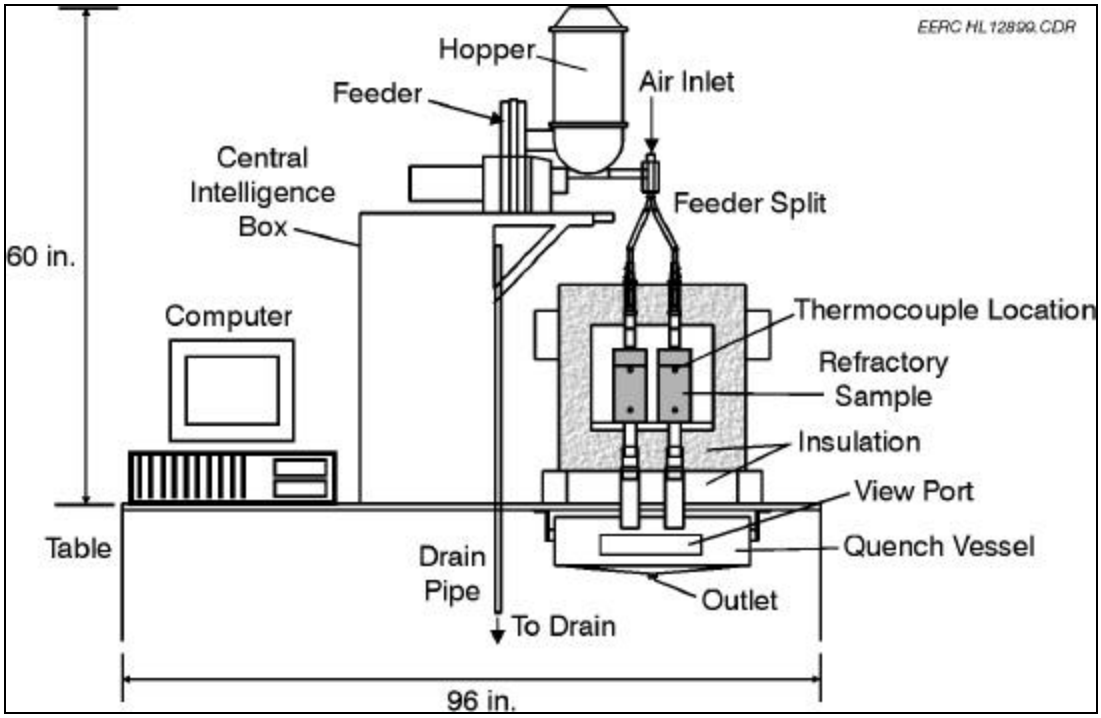

Figure 1 Schematic of the DSAF

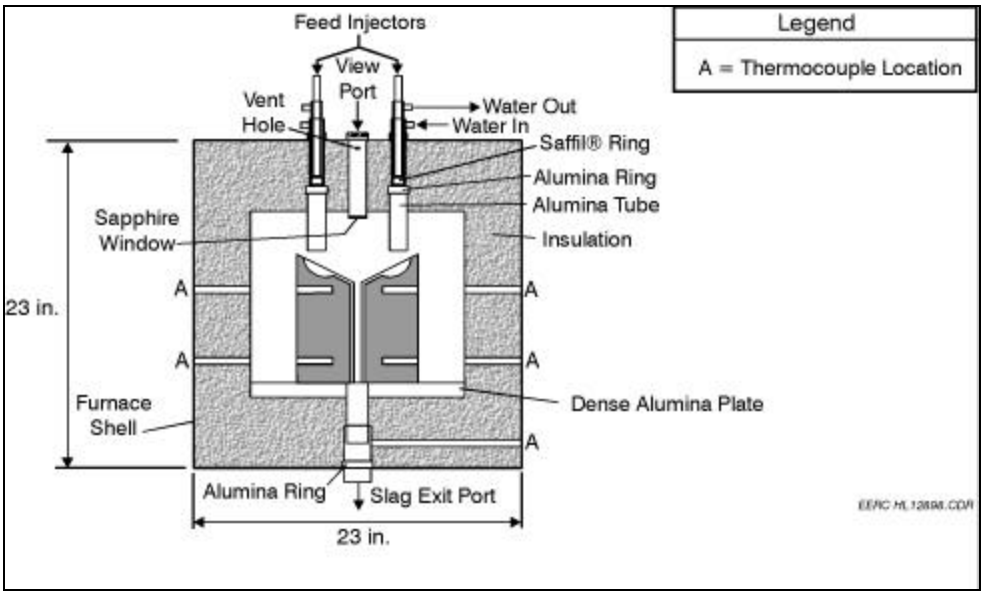

Figure 2 Schematic of the Inside of the DSAF with Refractory Block in Place

Four slag injector feed ports and two view ports are located on the top of the furnace. Each view port is a 6-in.-long 99.8% dense recrystallized alumina ceramic tube with a Vycor™ window at the cold junction and a sapphire window at the high-temperature junction. The injector feed tubes are designed in two stages: a water-cooled stainless steel tubing that goes 22 in. into the furnace insulation and a 4-in. alumina tube that hangs 2 in. into the furnace chamber. Two exit ports for the spent slag are located at the bottom of the furnace. These are made of the same material as the view port. The spent slag exits through ceramic tubes into a water quench vessel.

The Ktron™ feeder is a precise low-rate volumetric feeder with a full hopper agitation made of 316 stainless steel material. The Ktron™ feeder can be controlled by either manual or remote methods. The transfer of the slag granules from the feeder is controlled by a double intermeshing set of augers. At the end of the transfer tube is a custom-designed feeder splitter to perform a 1- to 2- to 4-way split of the slag granules into the four feed injector entry ports, which are connected by high-temperature Tygon™ tubing to the water-cooled stainless steel feed injectors. The feeder is calibrated to deliver a slag area flow rate per unit refractory equal to that projected for the pilot-scale slagging combustor being used at the EERC in the Combustion 2000 work. The calculated value was 51 g of slag through each feed injector entry port during a 1-hour time period, hence a total of 204 g of slag for all four entry ports. The feeder hopper can hold about 50 pounds of slag material, or enough for 100 hours of operation.

An air entry port is located on the top of the splitter, which is connected to the slag feeder. An air flow rate of 125 cm^3/min is used for each entry port for DSAF experiments. The primary function of the air is to keep the hot air from rising up through these feed entry ports and, secondly, to cause a positive air pressure for both the slag granules and melt to flow down through the exit ports.

The refractory test blocks are 4 by 4 by 9 in. tall with a 30-degree incline on the top surface. On this inclined surface is a well, 13 by 1/8 in. deep, which is drained by a 2-in.-wide by 3-in.-deep open vertical channel. The blocks are cast in rubber molds, cured, then prefired in the DSAF before the slag is

introduced. With this design, for a slag with a viscosity of 100 poise using the feed rate stated above, the slag film thickness during a test is approximately 1/3 mm.

Results and Discussion

A total of fifteen commercial and eight experimental castable refractories have been tested in the program, along with three types of brick materials. The castable refractories have included alumina-bonded silicon carbide (SiC), chrome–alumina, and alumina-based materials. The SiC-based materials are useful to only 2552? F (1400? C) because above that temperature they are prone to active oxidation. Although useful to protect a heat-exchanger, because in such a case they would be actively cooled, they are not useful as an uncooled material and therefore are not discussed in this paper. The chrome–alumina castable did show good corrosion resistance at higher temperatures, but because of environmental concerns about leaching of chrome from the spent material, work with these materials was limited, and therefore is also not discussed in this paper.

Comparison of Static to Dynamic Results

Figure 3 shows a comparison of static and dynamic corrosion blocks for three commercially available and one experimental refractory after testing with Illinois No. 6 slag. The static blocks were tested for 100 hours at 1700 C, the larger dynamic blocks for only 5 hours at 1600? C. The results for static blocks are typical of all alumina castable refractories tested by this method, in that the slag completely soaks into the blocks. A close analysis of penetration depth and surface recession indicates that the Plicast 96 was the least resistant to damage during the static tests. However, observation of the dynamic corrosion test blocks shows that the Plicast 96 material performed the best of all the commercially available materials. In fact, the other three materials performed so poorly that slag did not even build up in the slag well, but instead dissolved rapidly through the block itself.

These results indicate that when the slag soaks into the block, the static test is not useful for differentiating between performance of the materials under dynamic conditions. They also show that higher-alumina-content refractories such as the Plicast 96 survive flowing acid slag corrosion at these temperatures much better than those with lower alumina levels. In addition, SEM analyses showed that the primary attack was against the cement material, not the aggregate. The cement for the three poorly performing materials was calcium aluminate-based, whereas for the Plicast, it is based on hydrated alumina. Therefore, after these results, static tests were abandoned, as were lower-alumina-content refractories. For most of the ensuing tests, the EERC worked with the manufacturer of the Plicast refractory, Plibrico Company of Chicago, to test several experimental 98% and 99% alumina formulations using Alphabond, a hydrated-alumina cement manufactured by ALCOA.

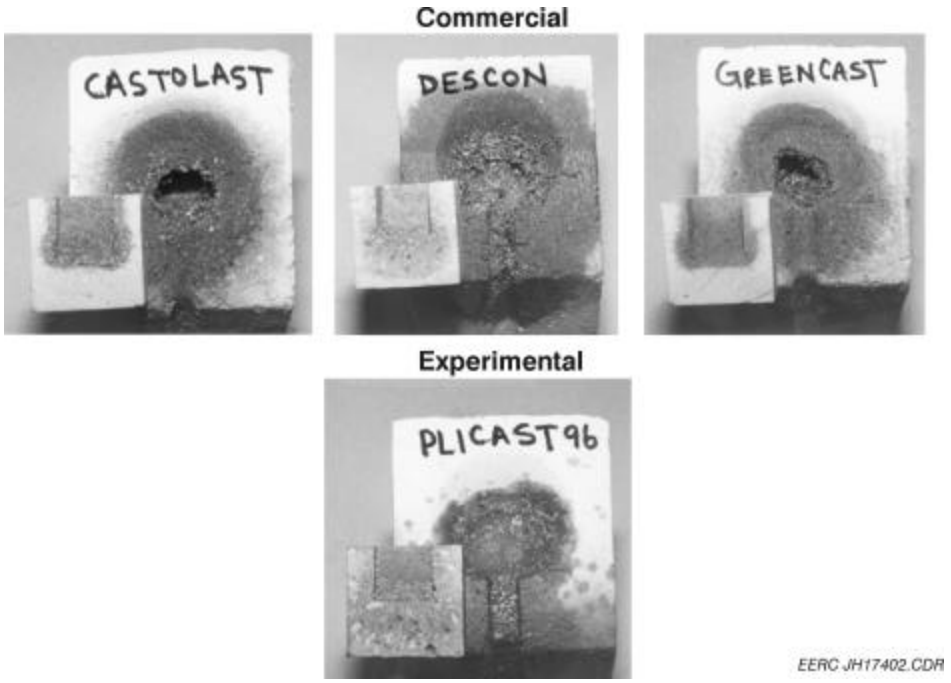

Figure 3 Comparison of Static and Dynamic Test Results for High-Alumina Castable Refractories

The Effects of Reaction Temperature

One obvious way to reduce refractory corrosion rates is to reduce the surface temperature of the refractory either by subsurface cooling or by lowering the gas temperature. However, there are capital costs and efficiency penalties incurred in doing this. To determine the relative influence of a small variation in temperature on corrosion rates within the range of temperatures high enough for slag flow, blocks of Plicast 99 were tested with Illinois No. 6 slag at 1400? and 1500? C. It was not possible to test at lower temperatures with this slag because its viscosity was so high at 1400? C that it was prone to plugging the slag exit tube. Figure 4 shows the average surface recession within the flow channel as compared to the length of the test. The graph indicates two things. First, that corrosion rates by flowing slag are nearly linear, except for a slightly higher initial rate while the excess cement at the surface of the material is dissolved away. In addition, the graph shows that for a 100? C reduction in temperature, but still within the range of flowing slag, corrosion rates are cut nearly in half for this slag and refractory combination. However, corrosion rates were still too high, extrapolating to approximately 1.3 in. after 1000 hours.

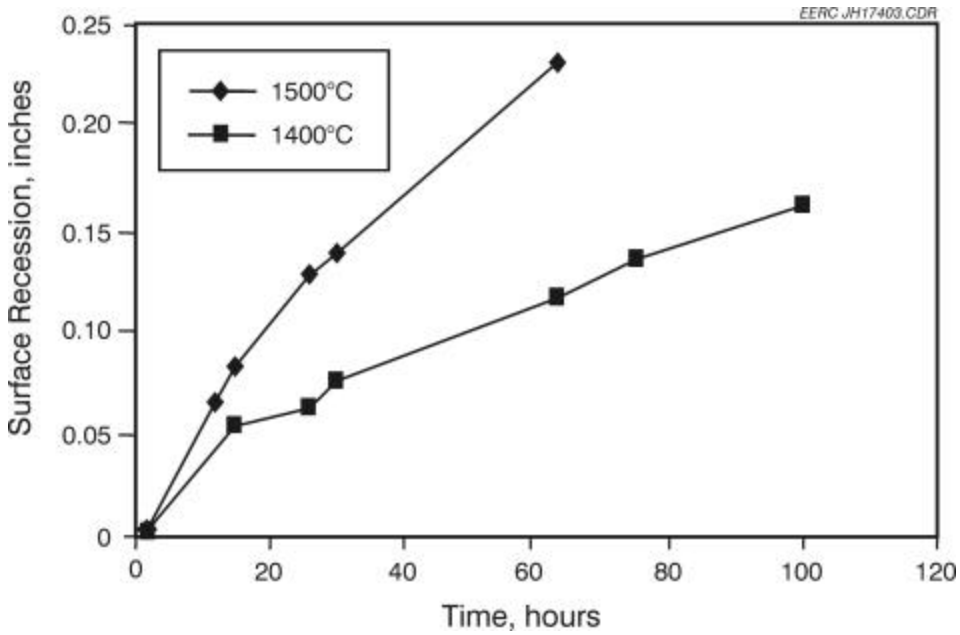

Figure 4 Corrosion Rate Versus Time and Temperature for Plicast 99 Refractory and Illinois No. 6 slag

The Effects of Coal Type

Tests in the pilot-scale flowing slag combustor system at the EERC has shown that more basic coal slags are much more corrosive to the Plicast refractory than the more acidic bituminous coal slags like the Illinois No. 6 slag. The basic slags are especially corrosive to new patches of refractory. However, older regions of refractory that have been previously exposed to less corrosive slags and fired to higher temperatures for longer times are much less corroded. To determine the effect of firing temperature on corrosion by a basic slag, blocks of the Plicast 99 were fired at 1500? C and 1600? C and exposed to flowing slag formed from lignite provided by the Coal Creek Station power plant in North Dakota. Figure 5 shows the blocks after only short exposures to the slag. Although firing to the higher temperature did reduce corrosion somewhat, in both cases the lignite slag penetrated the refractory and formed secondary crystallization products that expanded and caused the refractory to burst.

Figure 5 demonstrates that hydrated alumina is not a suitable binder for refractories exposed to lignitic slags. Therefore, four other refractories provided by Plibrico and ALCOA were tested with slag formed from lignite provided by the Milton R. Young Station (MRYS), North Dakota. Plibrico Plicast 90 MAV contains 10% magnesium–aluminate spinel and 90% alumina. The remaining three are from ALCOA. SFL214AB3 contains 12% magnesium aluminate spinel. SFL224AB3 contains 29% magnesium aluminate spinel. AFL204AB3, an all-alumina self-flowing castable, is made with Alphabond 300, an experimental cement produced by ALCOA.

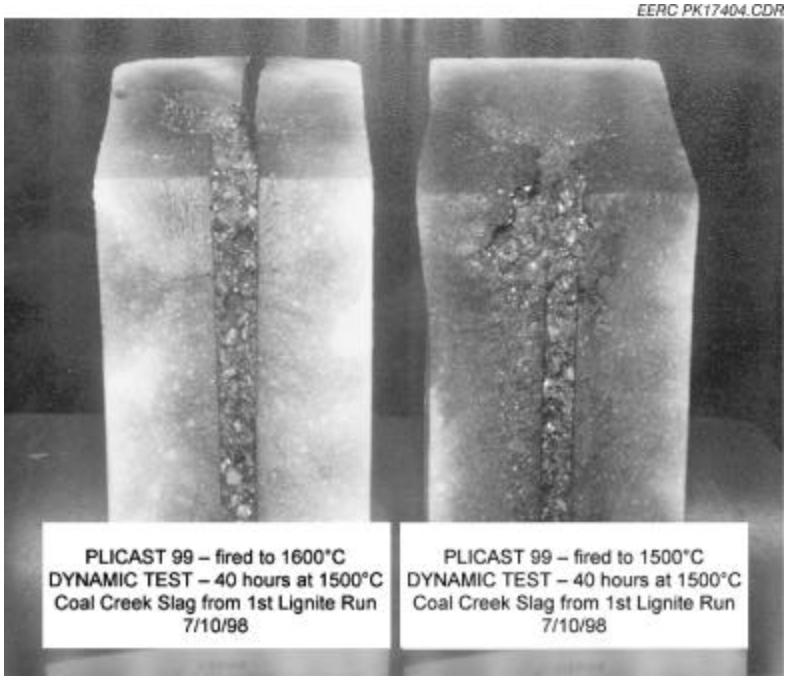

Figure 5 Blocks of Plicast 99 after Corrosion Testing with Lignitic Slag

The blocks were prefired to 1625?C (2957? F) then tested at 1500? C (2732? F) using MRYS slag. The feed rate was approximately 50 grams per hour per injector. Figure 6 is a plot of the average measured recession versus time for the four samples. Since the rate of recession was so rapid for all four samples, the

tests were stopped early. In contrast to the all-alumina Plibrico castables tested previously, the magnesium–aluminate spinel materials did not swell and crack. However, corrosion rates with the lignite slag are far too rapid even for the new samples, so none are recommended for use in a slagging combustion system firing a lignite. In future tests, all four castables will be tested with Illinois No. 6 slag at 1500? C (2732? F) to compare the recession rates with the other castables tested in the DSAF.

Effects of Refractory Additives

Alumina forms a complete series of crystalline solutions with the lanthanide or rare-earth oxides (REOs). Perovskites, $ReAl_2O_3$, where Re is a rare earth such as Y, La, Nd, Ce, Pr, Pm, Sm, or Eu, and the garnets, $Re_3Al_5O_{12}$ where Re can be Y, Tb, Dy, Er, Tm, Yb, or Lu, are all stable, high-melting-temperature materials. Therefore, yttria, neodymia, and lanthana were mixed in all combinations at proportions of 0.5% and 2.0% with the Plibrico 98 in order to determine if they could increase the corrosion resistance of the refractory to bituminous coal slag. Phase diagrams were used to identify stable high-melting-temperature materials within the lanthanide–alumina series that could modify the bonding phase of the alumina-based refractory. Two mechanisms for reducing corrosion were investigated. One was the formation of corrosion-resistant surface layers. The other was increased sintering to raise strength and seal continuous pores that would reduce slag penetration.

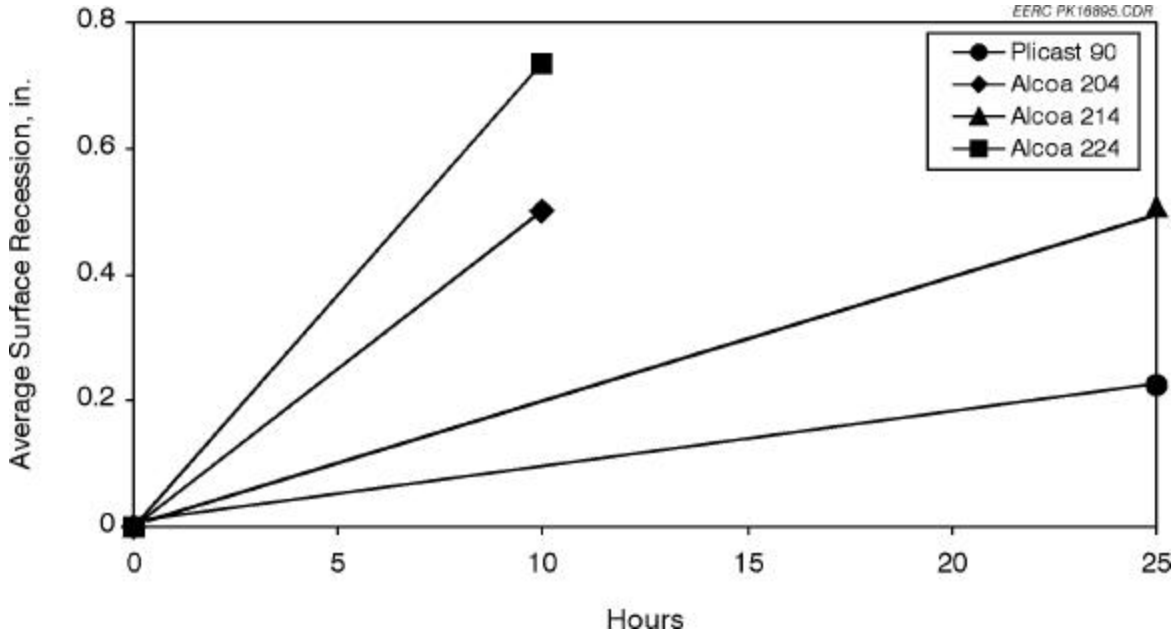

Figure 6 Plot of Average Recession Versus Time for Alumina and Magnesium Aluminate Castable Materials after Dynamic Corrosion Test Using MRYS Lignite Slag

Three different processing methods were employed for fabricating the test samples. These included bulk mixing, impregnation, and surface coatings. Static cup tests were used initially to determine if the REOs formed corrosion-resistant surface layers that would prevent slag penetration. However, the Illinois No. 6 slag readily penetrated each of the blocks at 1500? C, although the yttria-doped material showed the least penetration. Figure 7 shows a yttrium–aluminum–garnet (YAG) phase formed inside the yttrium-doped block. Although it survived the corrosion test, it was discontinuous and did not provide a barrier to

penetration of the slag. Tests of pure YAG crystals showed that they were even less resistant to slag corrosion than the base alumina refractory. Therefore, the REO additions were not useful in developing corrosion-resistant layers in the alumina refractory. In addition to the corrosion tests, three-point modulus-of-rupture (MOR) tests were performed using the standard ASTM C 133 procedure to determine if the addition of an REO improved the strength of the refractory. A strength increase would show that the refractory was more resistant to erosion and also that increased sintering had occurred, which would imply a reduction in porosity. However, none of the REO additions increased the strength of the materials, so work with REO additions has been dropped.

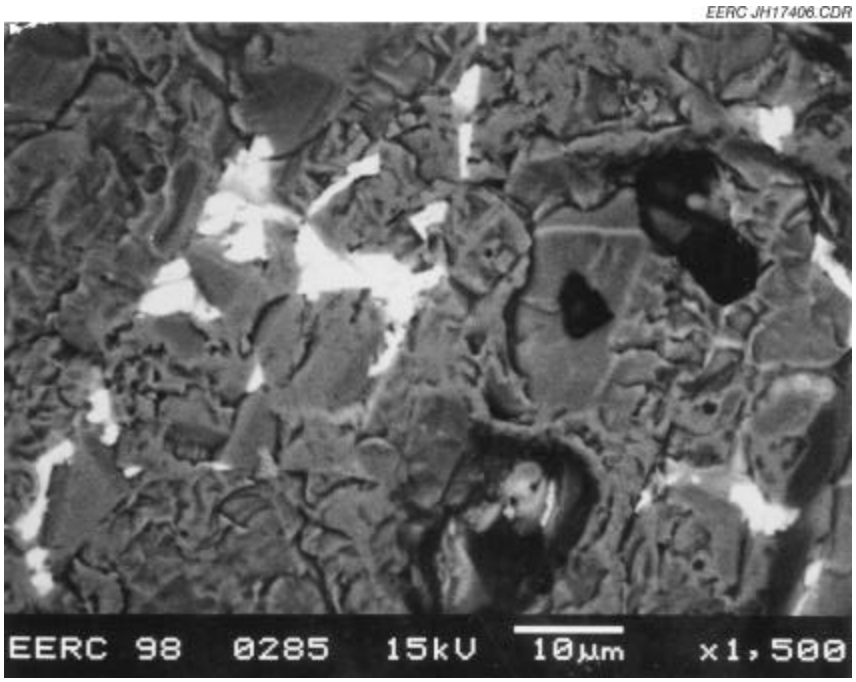

Figure 7 The Formation of YAG with the Plicast 99 Refractory

Slag Additives

In all DSAF corrosion tests, it was found that surface recession at the bottom of the refractory block was always much less than at the top. Analyses of the spent slags also indicate that the slag is enriched by several percent in the material making up the refractory block. This indicates that as the slag dissolves some of the refractory, it becomes significantly less corrosive. To determine the relative effect of small amounts of additives on slag corrosivity, Plicast 99 blocks were tested at 1500EC with Illinois No. 6 slag with and without 3% alumina added. Figure 8 illustrates that even with such a small amount of additive, the corrosion rates dropped by a factor of three. This occurs for two main reasons: First, laboratory measurements demonstrate that a 10% alumina addition to this slag doubles its viscosity from 100 to 200 poise at this temperature. Since slag flow velocity in a thin film varies inversely with the cube root of the viscosity, such an increase would lead to a velocity increase of approximately 25% and, subsequently, higher erosion. However, only 3% alumina was added to the slag for the corrosion test, so we would expect that the velocity increase would be less than 25% and probably not sufficient to decrease the loss rate by a factor of three. Another mechanism by which the alumina addition may decrease the corrosivity of the slag is

simply by increasing its concentration to near that of saturation. As the saturation level is approached, dissolution rates would be expected to decrease markedly.

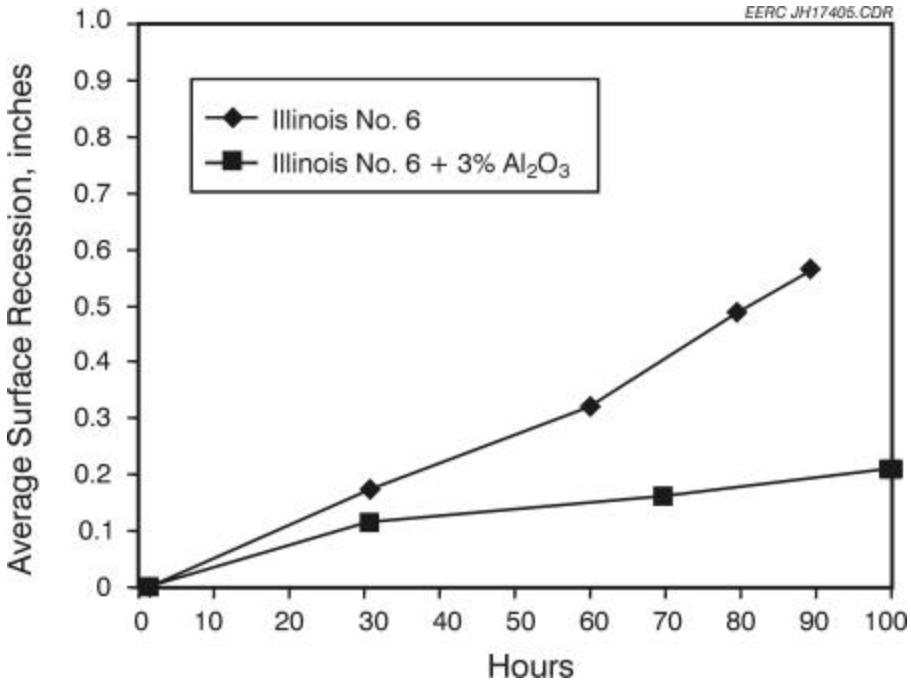

Figure 8 The Effect of Alumina Addition of the Corrosion of Plicast 99 by Illinois No. 6 Slag

Conclusions

Static corrosion tests are poor indicators of refractory performance when the slag fully penetrates into the refractory as it does for castable alumina-based materials. Instead, dynamic tests where the slag flows over the refractory are much more indicative of performance in a large-scale application. At temperatures near 1500EC, alumina-based cements provide acceptable service for testing purposes, whereas calcium aluminate cements do not. However, none of the refractories were acceptable for long-term commercial service. No refractory is universal in performance toward all slags. Alumina–cement refractories perform much better with acidic slags, but are easily penetrated by basic slags and burst through secondary crystallization. Alumina refractories with magnesium aluminate spinel additions perform better than pure alumina materials with more basic slags, but still do not provide adequate corrosion resistance. However, pilot-scale experience indicates that firing the refractory to higher temperatures, and especially coating it with more benign aluminosilicates, may substantially increase the lifetime of refractories exposed to basic slags at 1500EC. Rare-earth element additions to 99% alumina castables did not increase corrosion resistance or sintered strength. The most effective means of reducing alumina castable corrosion resistance may be addition of small amounts of alumina to the slag. An Illinois No. 6 slag to which only 3% alumina was added corroded an alumina castable by only one-third as much as the original slag at 1500EC.